

Winter 1-1-2010

Lecture 7, Part 2: Glass surfaces and coatings for new functionality

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Pennsylvania State University

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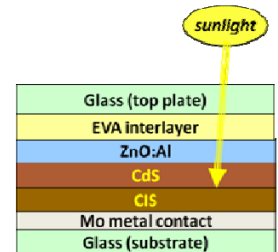
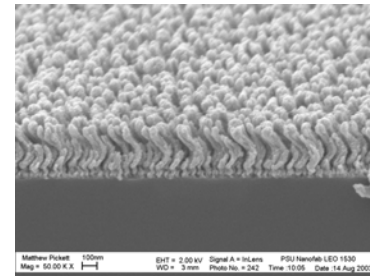
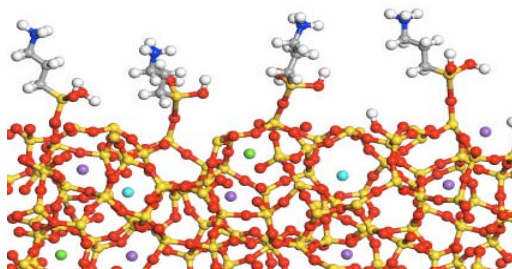
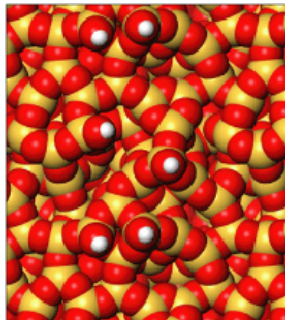
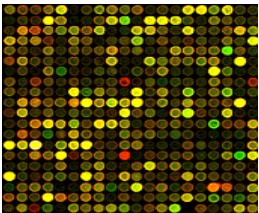
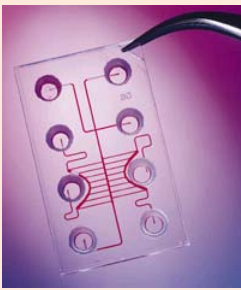
Glass Surfaces and Coatings for New Functionality

Carlo G Pantano

Department of Materials Science and Engineering
Materials Research Institute
Penn State University



CIGS = Copper Indium Gallium diselenide (CIGS)



PENNSTATE



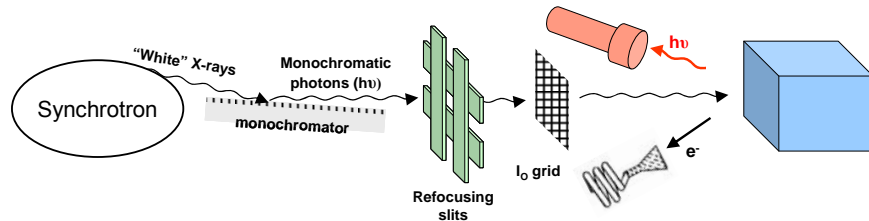
IMI Winter School
Zhejiang University
January 2010

Materials Research Institute

Center for Glass Surfaces, Interfaces, and Coatings

Important Roles for Glass Surfaces

- strength
- optical
- chemical defense
- substrate for coatings



Methods of Characterization

- surface composition (XPS)
- depth profiling (SIMS)
- surface roughness (AFM)
- organic adsorbates (FTIR/Raman)
- chemical structure (NMR and NEXAFS)
- surface charge (streaming potential)
- contact angle tensiometry
- adhesion (CFM)

Characteristics and Properties of Glass Surfaces and Coatings

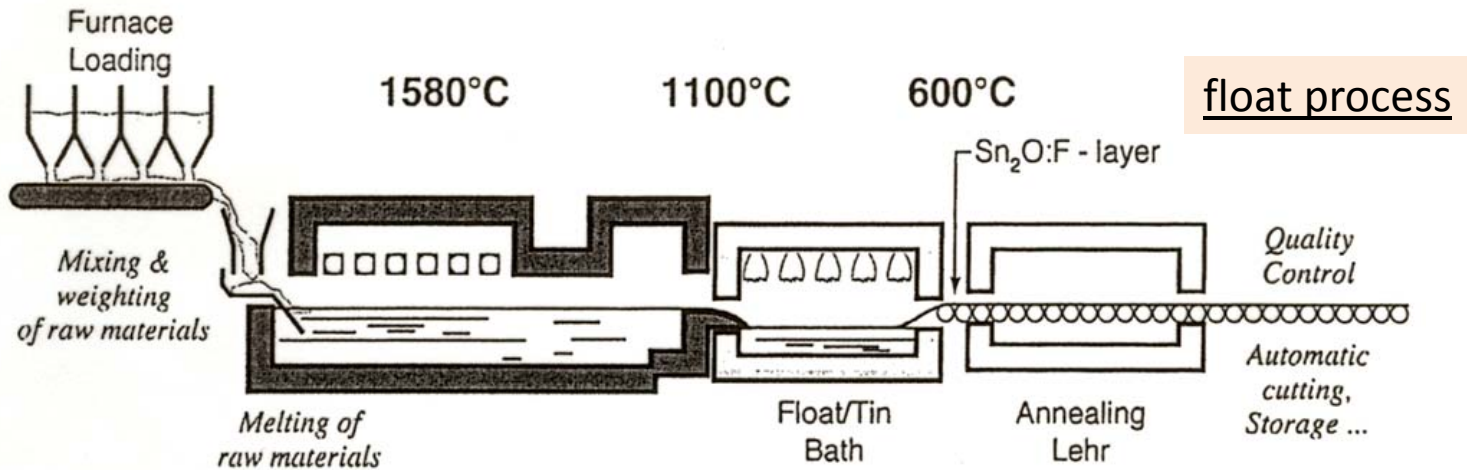
- surface composition
- chemical functionality
- contact angle/wettability
- surface charge and other surface forces
- porosity/roughness/specific surface
- cleanliness and chemical durability
- uniformity of ALL the above



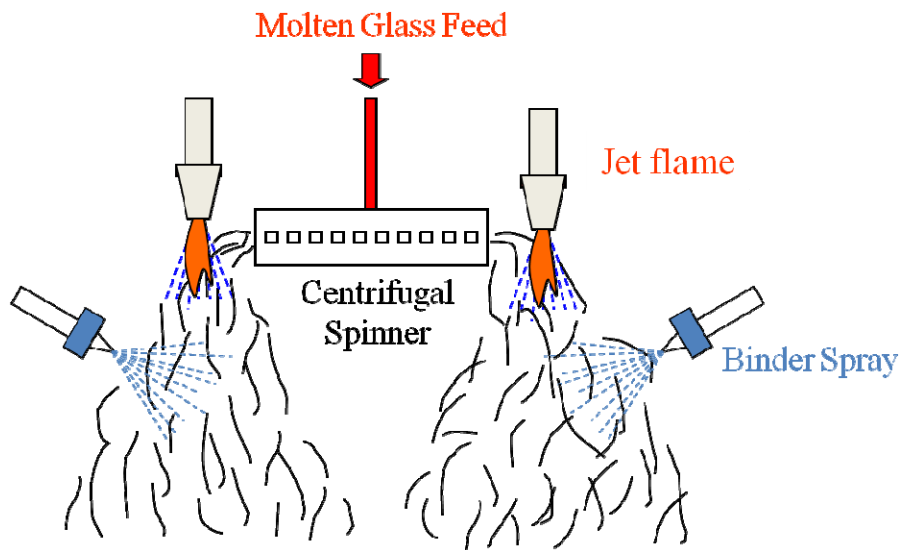
The composition, structure and properties of surfaces are determined by the process used to create the surface.

- Fracture surface
- Melt surface (frozen liquid)>> thermal history
- Ground and polished
- Chemically etched
- Plasma or ion-sputtered
- Vapor deposited

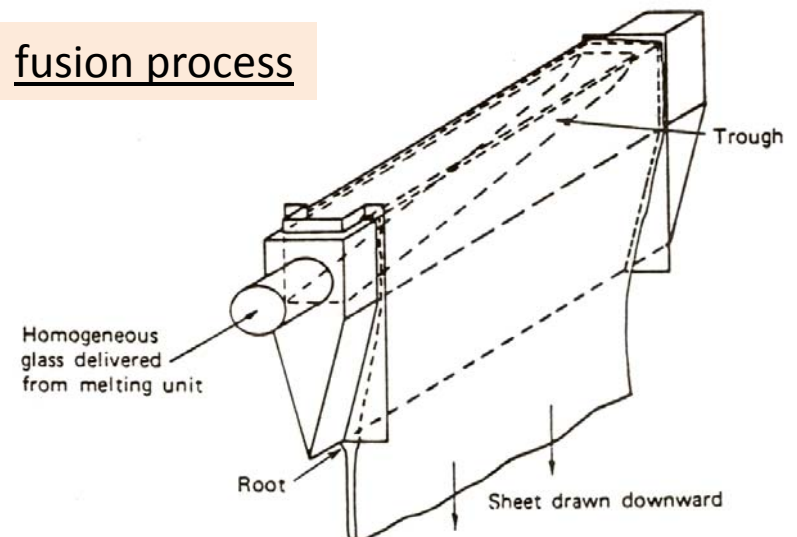
Manufacturing Flat Glass and Fiberglass>>> creating **SURFACE**



fiberglass wool



fusion process



Outline

Part 1: Fundamentals

- **Surface Structure and Adsorption**
 - fracture surface vs melt surface
 - silica vs multicomponent
- **Surface and In-Depth Reactions**
- **Surface Functionalization**

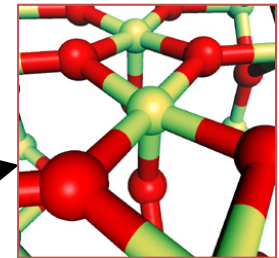
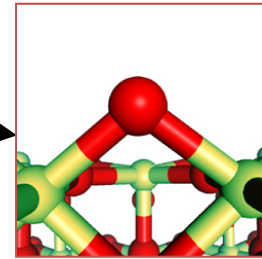
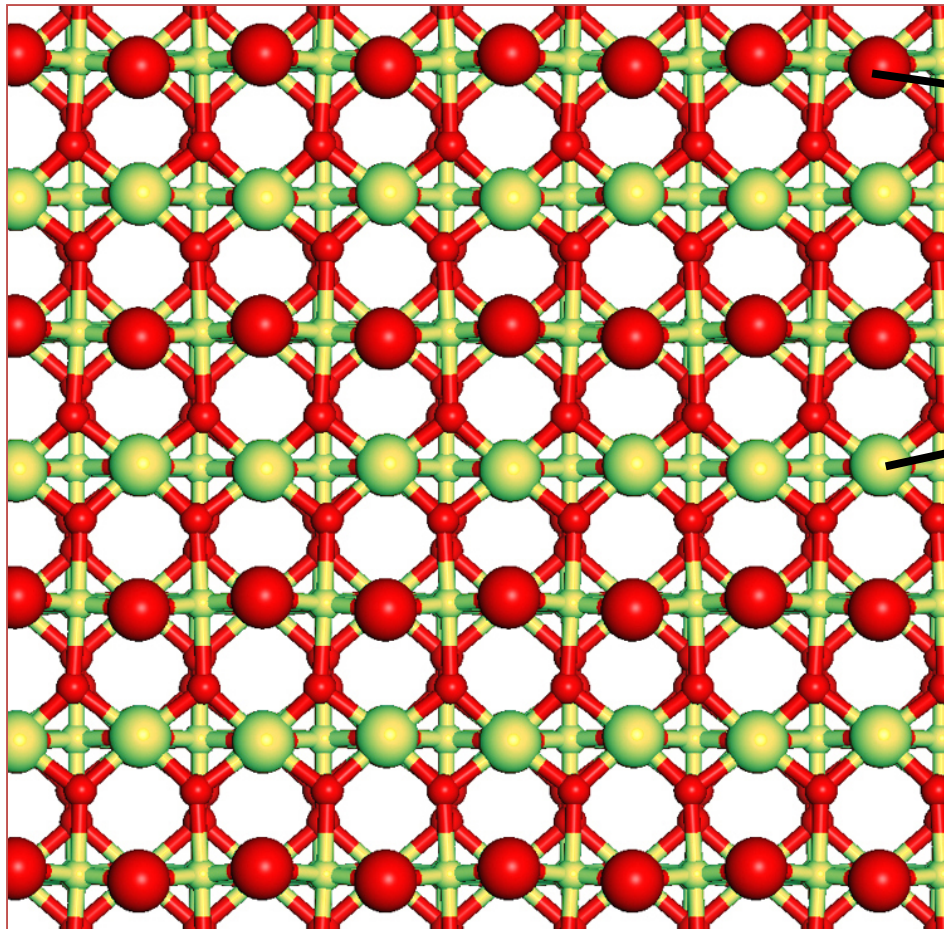
Part 2: Functional Surfaces

- **DNA Microarray Substrates**
- **Semiconducting Glass Surfaces**
- **Nanoscale Carbon Coatings**
- **Glass-Polymer Interfaces**

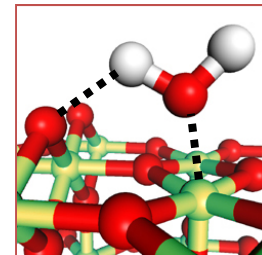
Crystalline Surfaces

Repeating arrays of nearly identical sites.

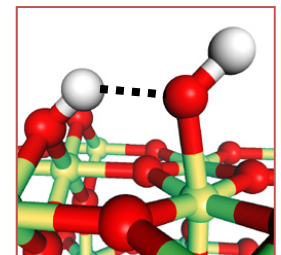
TiO₂ (110)



Physisorption

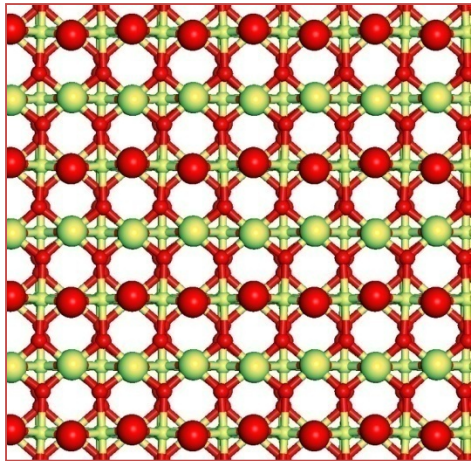


Chemisorption

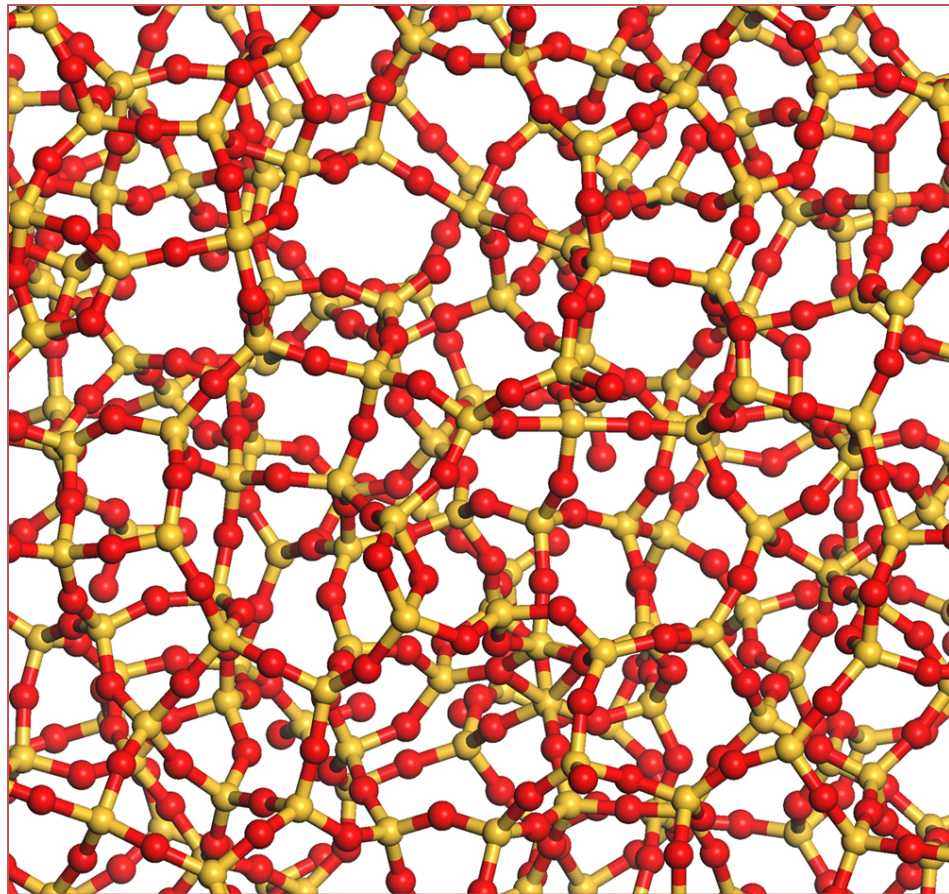


Glass Surfaces

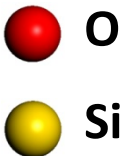
glass surfaces contain a continuum of **heterogeneous adsorption sites**.



TiO₂ (110)

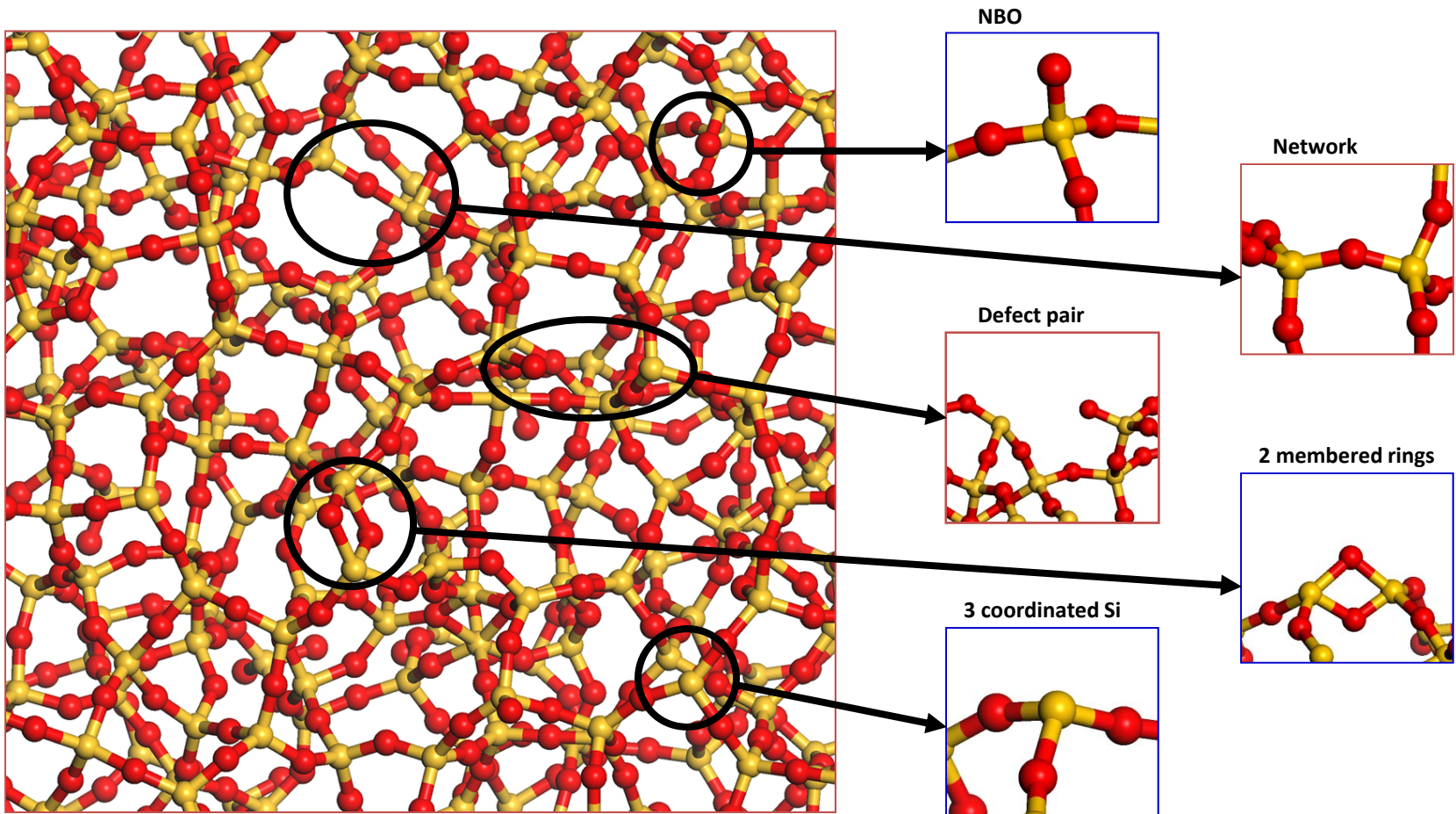


Silica glass



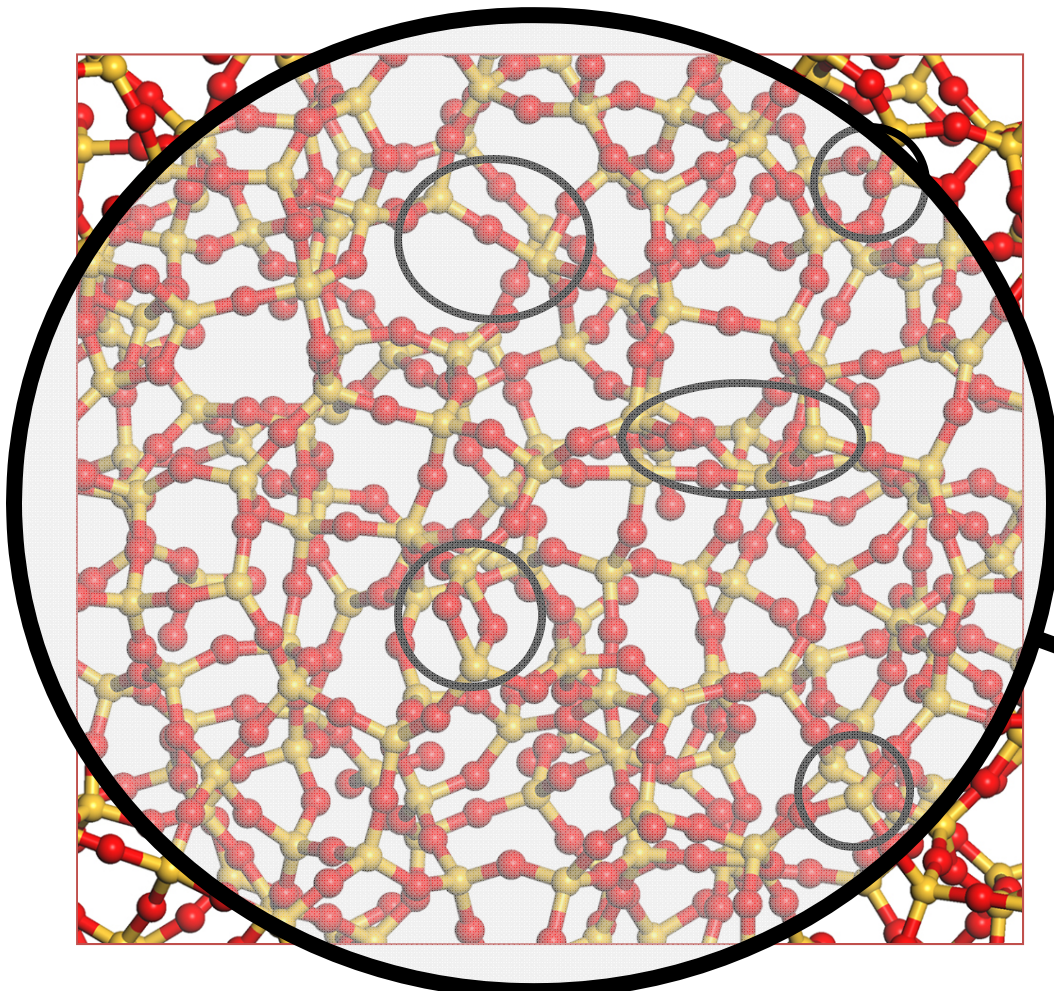
Glass Surfaces

the continuum of heterogeneous adsorption sites can be broken down into
a set of distinct types of adsorption sites.



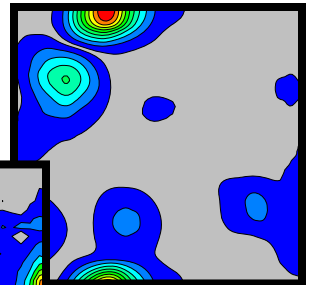
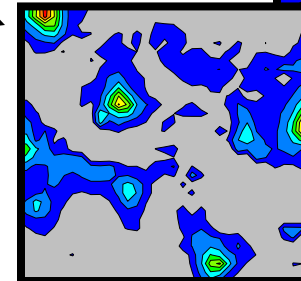
Glass Surfaces

Glass surfaces are made up of a vast collection of **heterogeneous adsorption sites**.



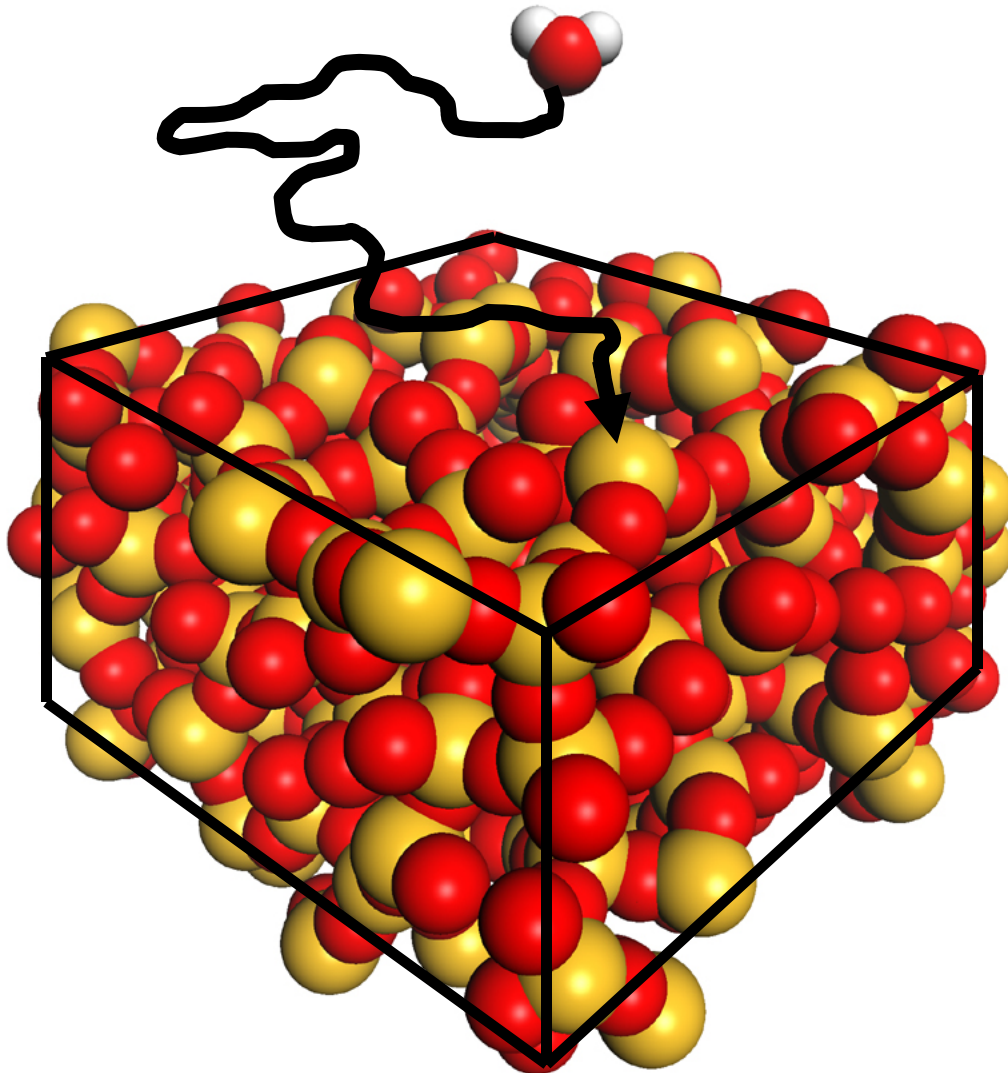
Modeling Goal: Map the adsorption properties of the surface as a continuous network of heterogeneous sites.

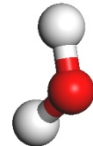
Physisorption



Chemisorption

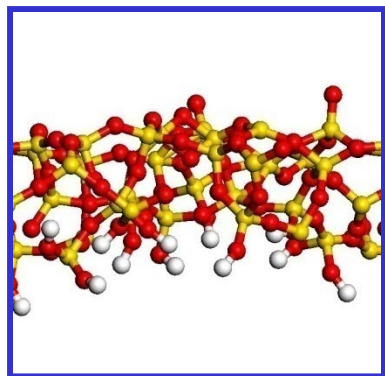
Modeling Surface Adsorption Sites Using Water (and other Polar PROBE Molecules)





Adsorption Investigated with DFT

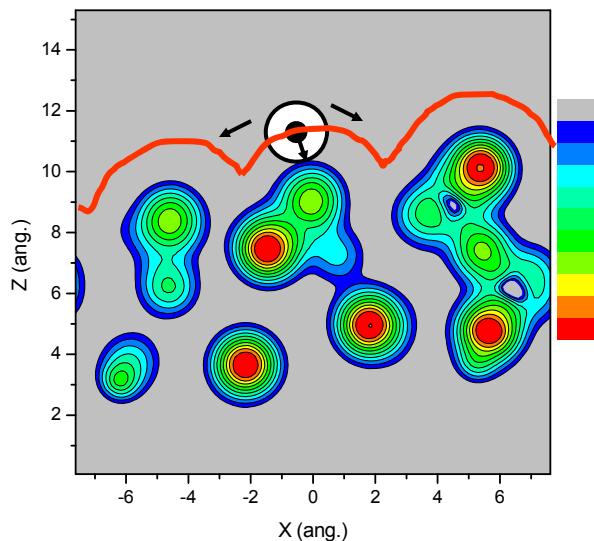
Start with a surface slab



(side views)

VASP

Create a surface profile



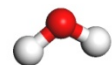
Calculate the electronic
“softness” of the charge
density

Find sites that are charge
donor/acceptor pairs

**Chemisorption
mapping**

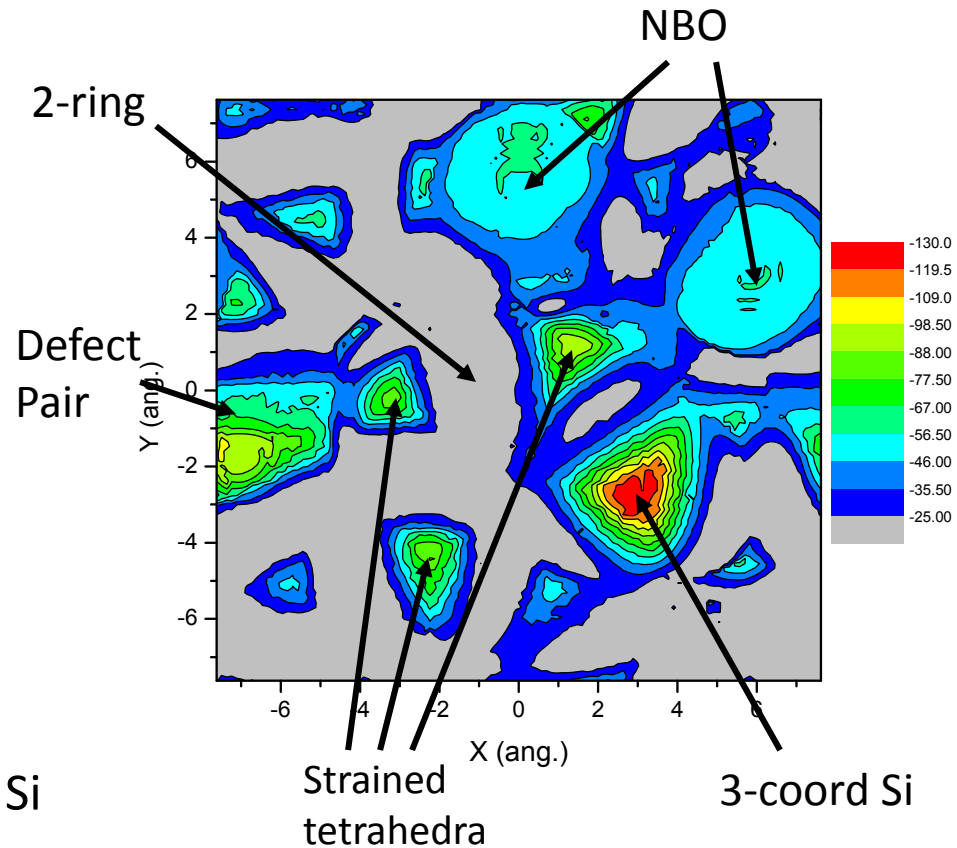
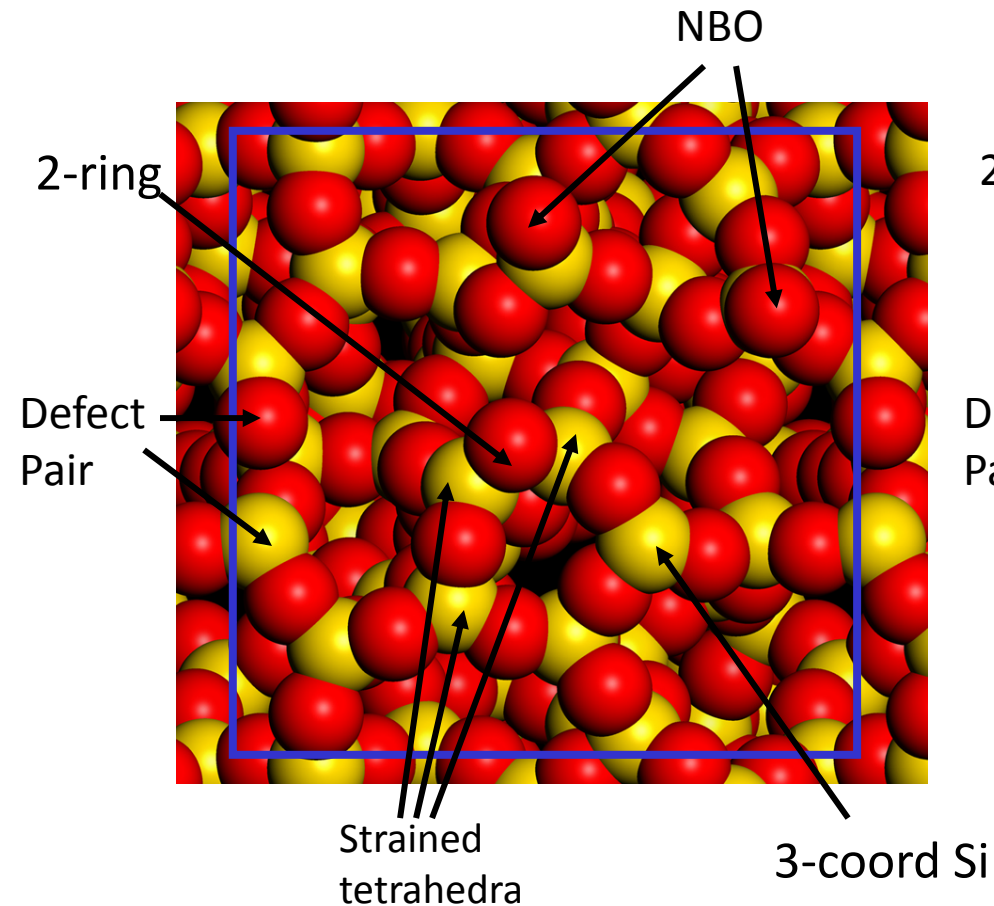
Multiply the gradient of the electric
potential by the dipole moment of
water (or any adsorbate)

**Physisorption
mapping**



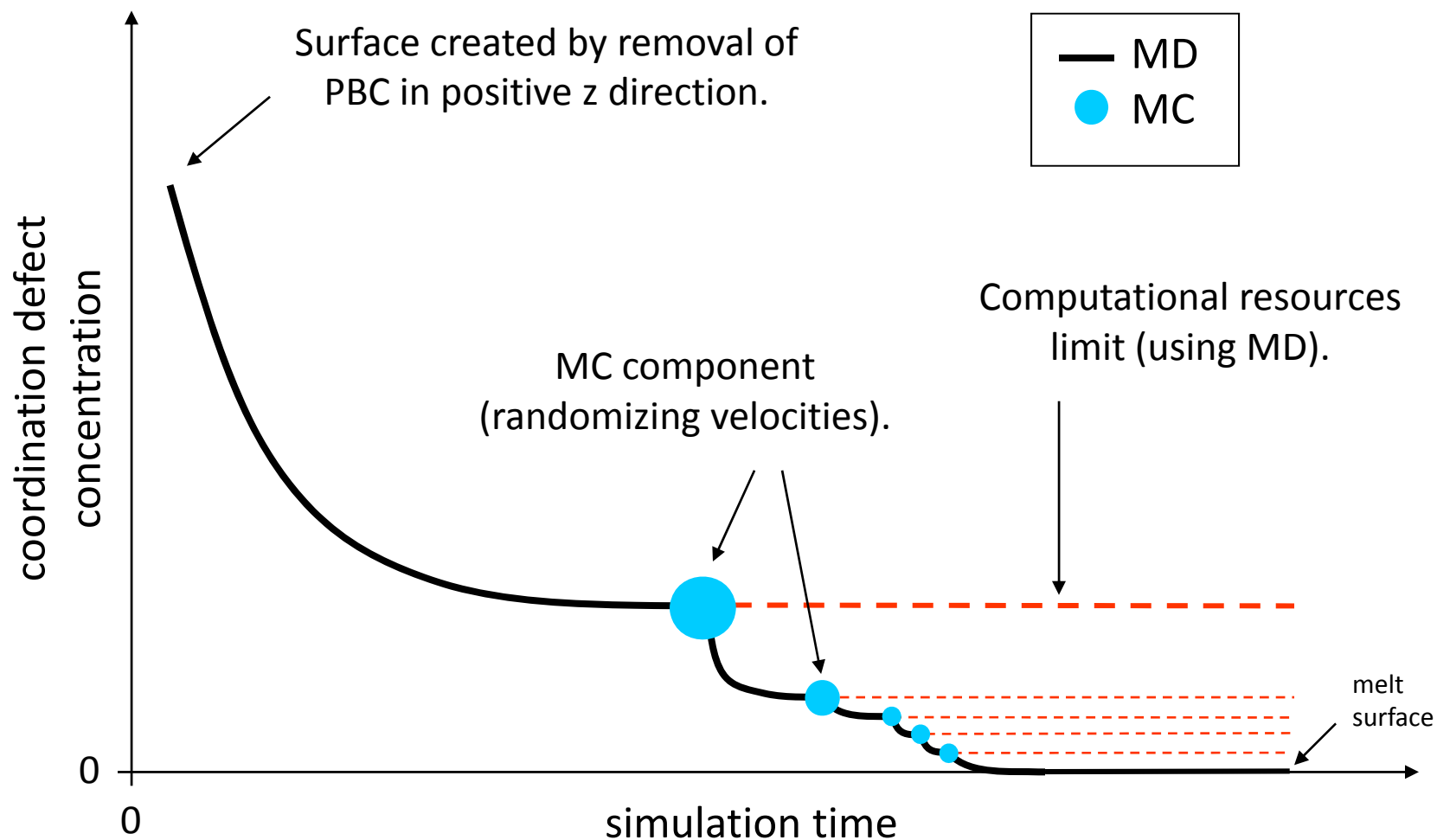
DFT Physisorption Mapping

Silica fracture surface



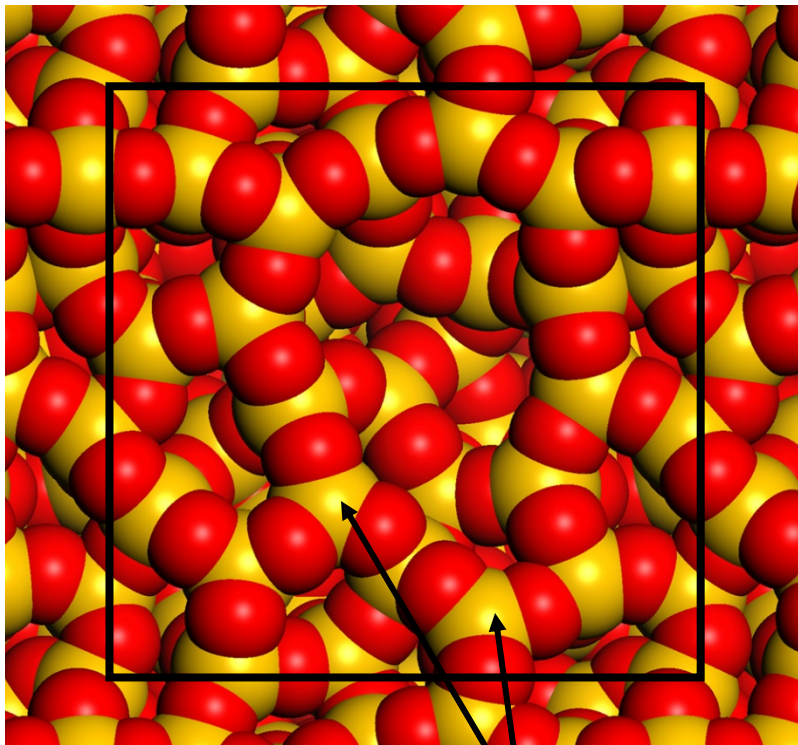
Modeling “Melt Surfaces”

Hybrid Monte Carlo / Molecular Dynamics (MC/MD)
for simulating coordination-defect-free surfaces

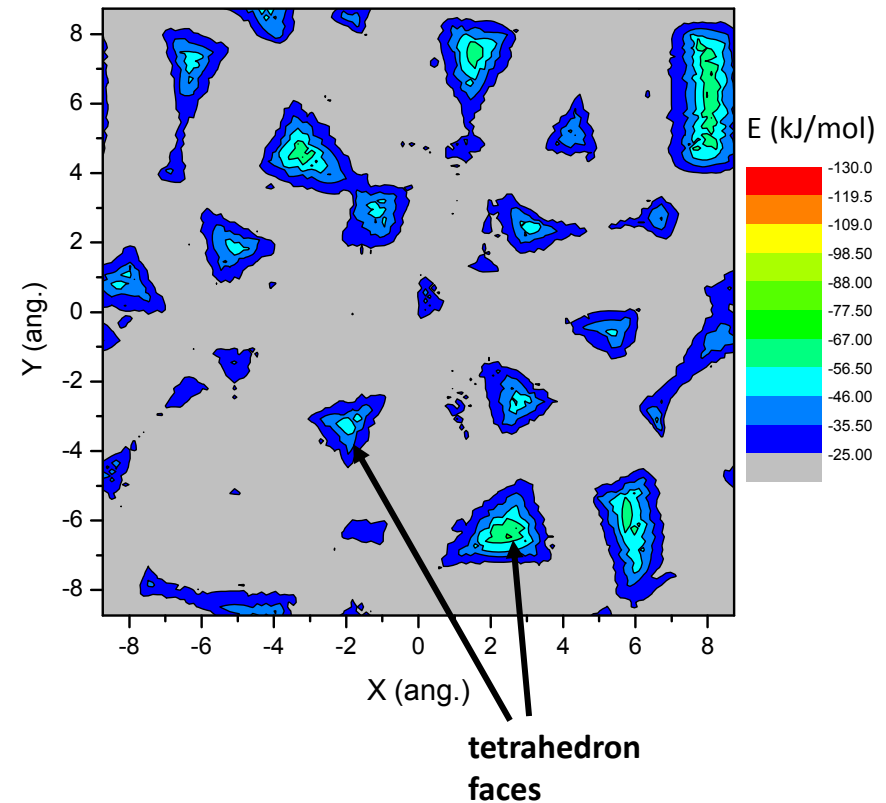


DFT Physisorption Mapping

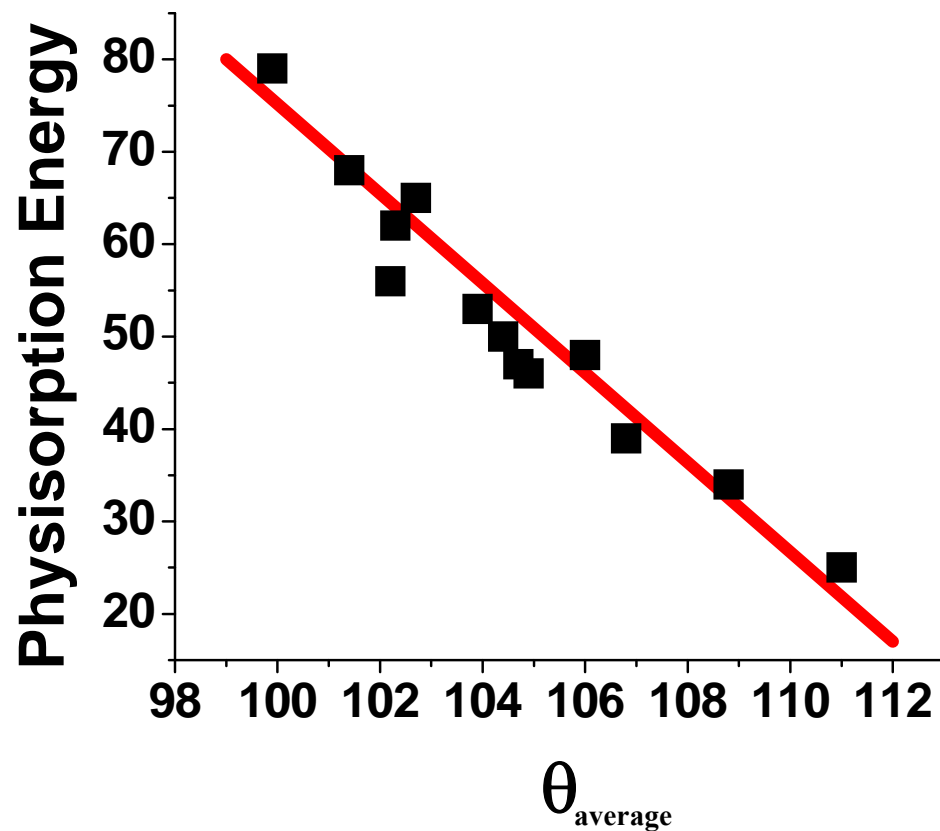
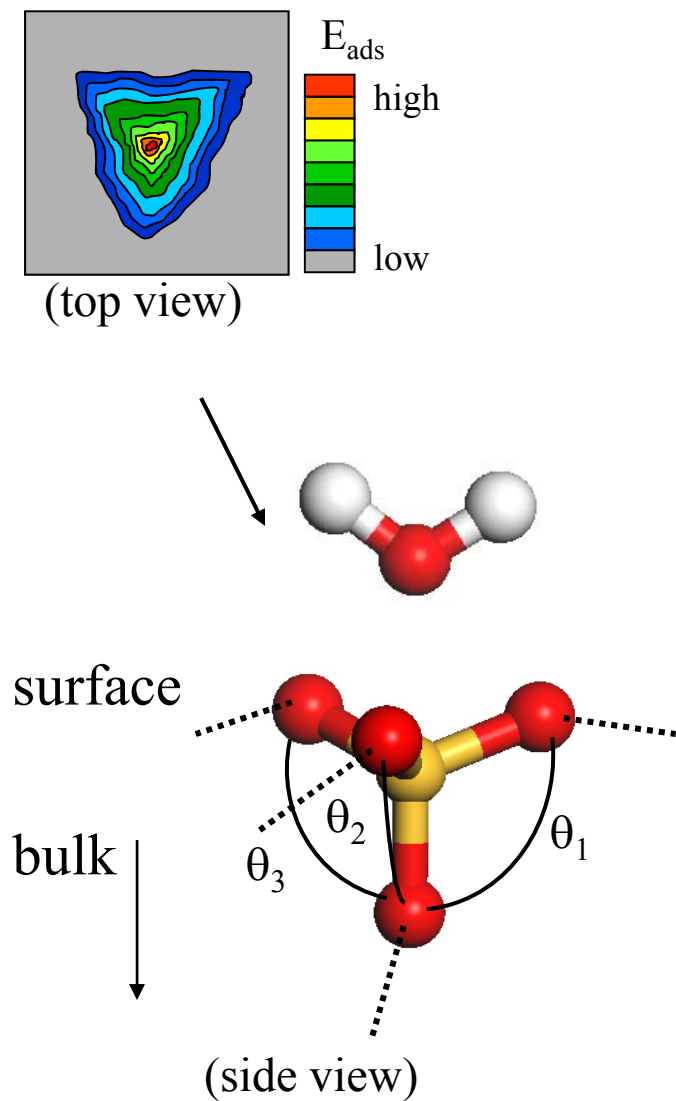
silica melt surface... relaxed to eliminate dangling bonds



tetrahedron
faces

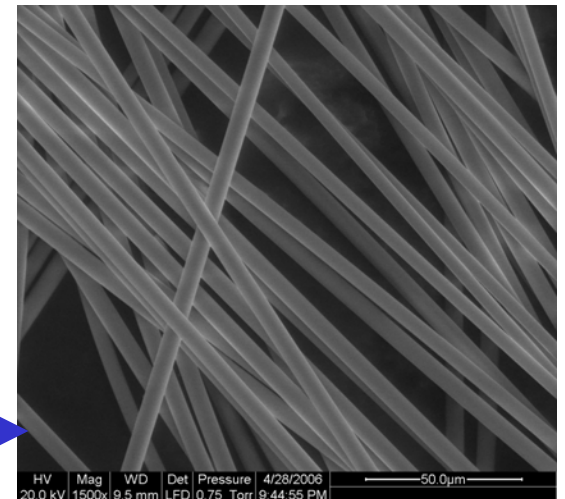
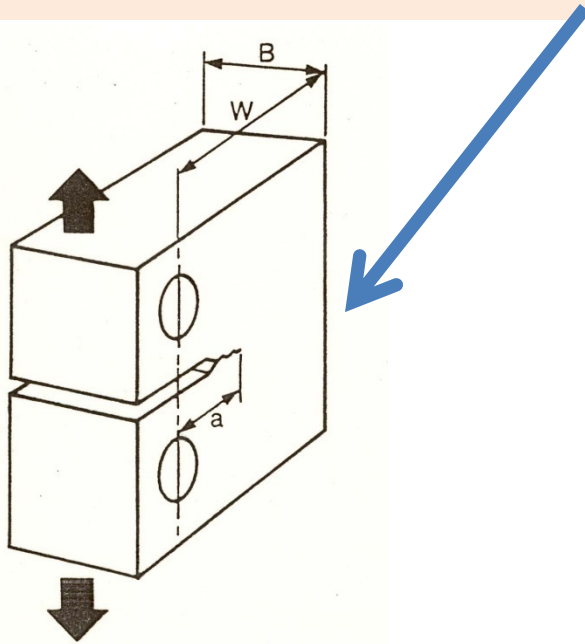


DFT Physisorption Mapping



Glass Surfaces for Research

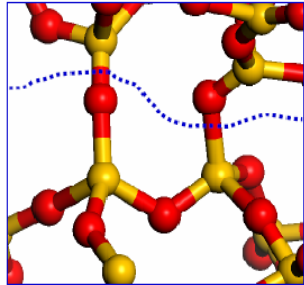
clean fracture surfaces and frozen melt surfaces



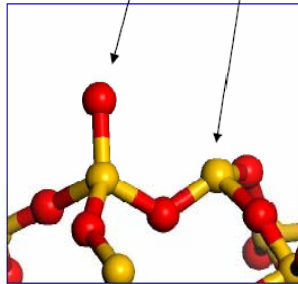
in-situ vacuum fracture surface analysis by static TPD SIMS

or fracture:

Before fracture:



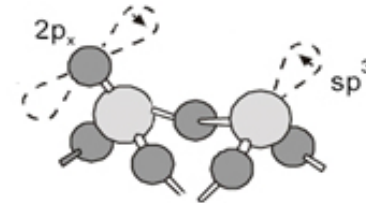
3-coordinated Si
and NBO



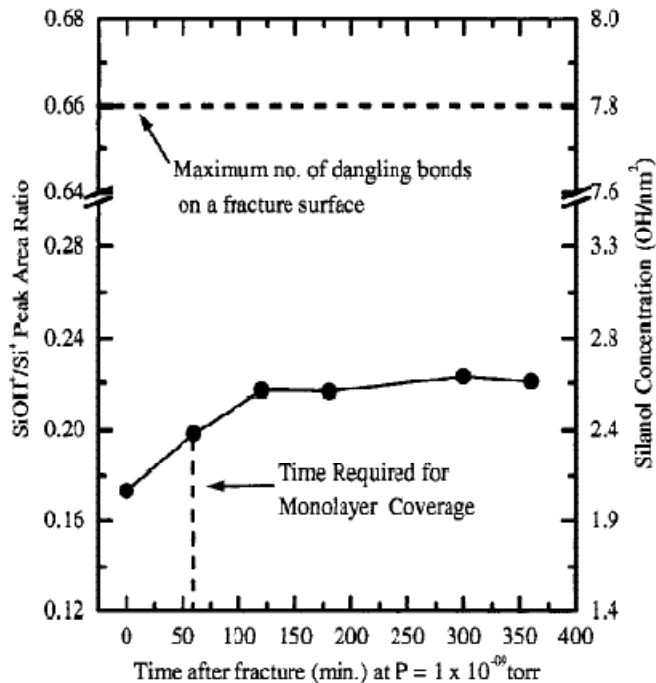
in-situ vacuum fracture surface analysis by ESR

NBOHC
(dangling oxygen
bond)

Generic E'-center
(dangling silicon
bond)



G. Hochstrasser, and J. F. Antonini, Surface Science **32**, 644 (1972)



$$(\text{Si} + \text{SiO})/\text{nm}^2 = \left(\frac{N}{v(\text{SiO}_2)} \right)^{2/3} \left(\frac{1}{N} \right) = 7.8 \text{ nm}^2$$

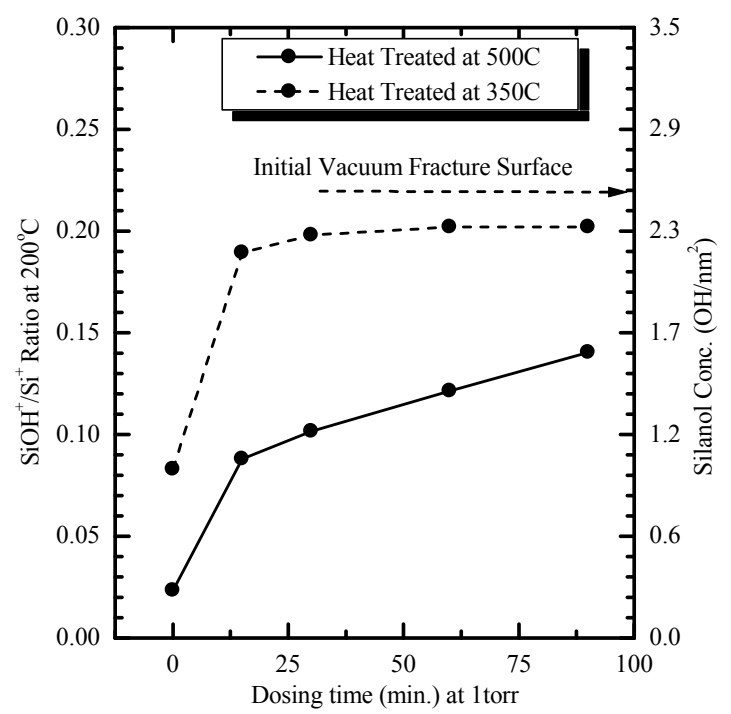
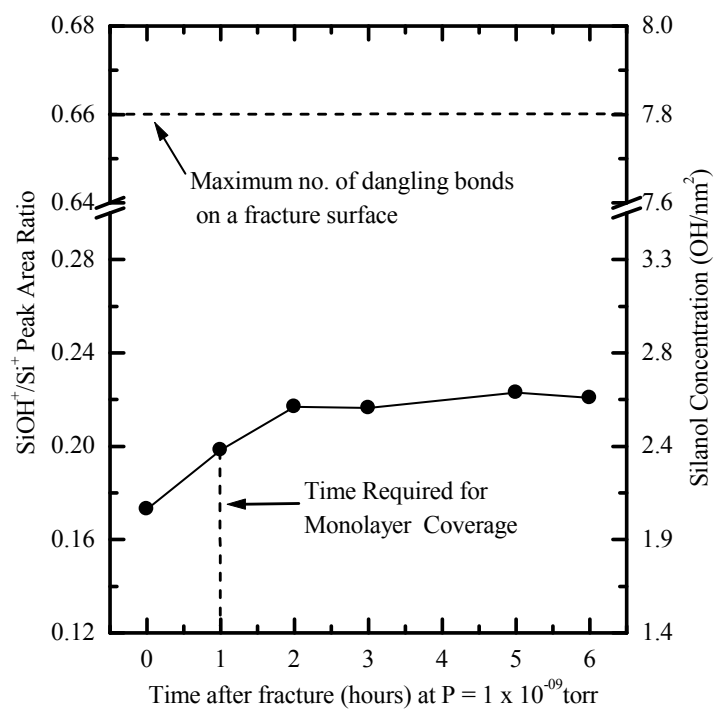
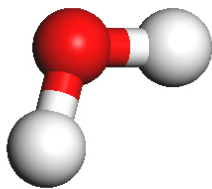
SIMS:
2.6SiOH/nm²
(33%)

ESR: 0.01
E'_s/nm²
dangling
(0.12%)

~5.2 bonds/nm²
re-constructed
(66%)

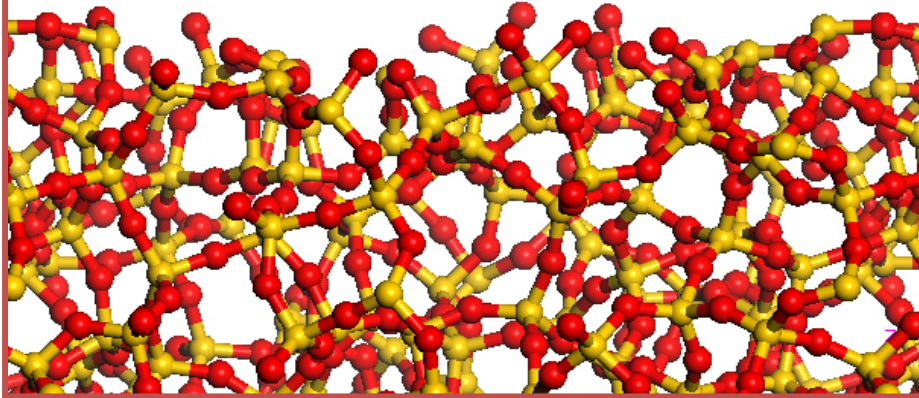


•experimental work on clean silica fracture surfaces showed dependence of water vapor adsorption kinetics on thermal history.

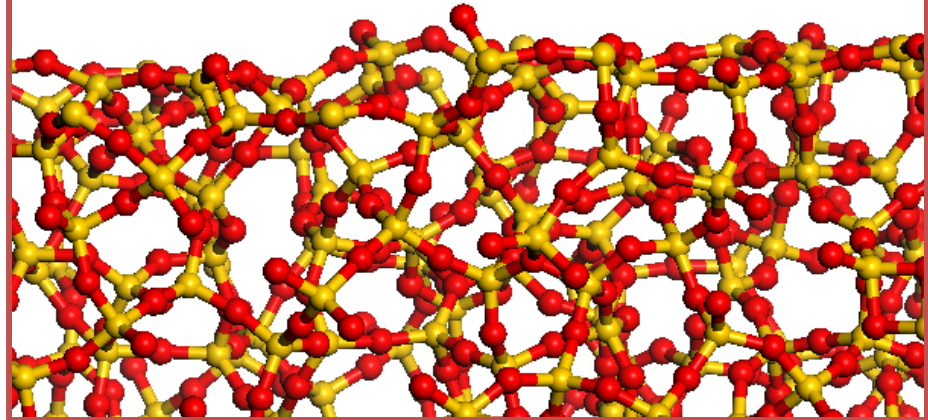


Glass Surface Structure Models

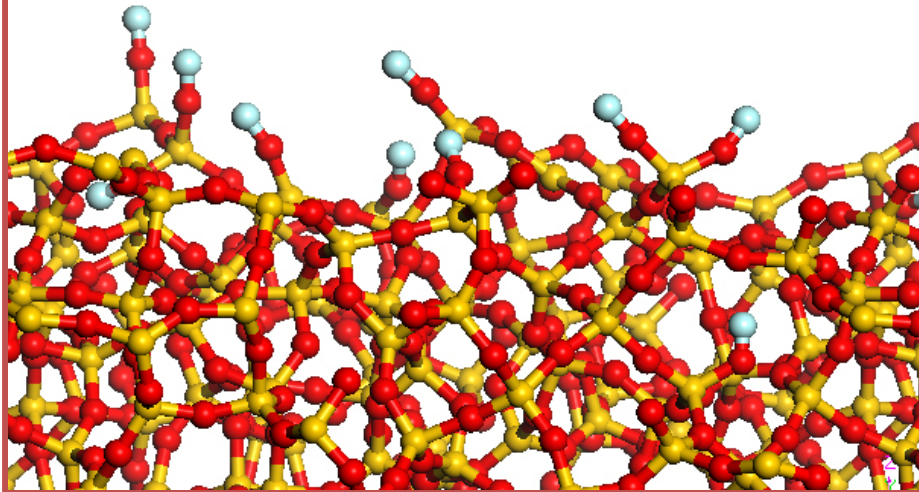
Silica at instant of fracture



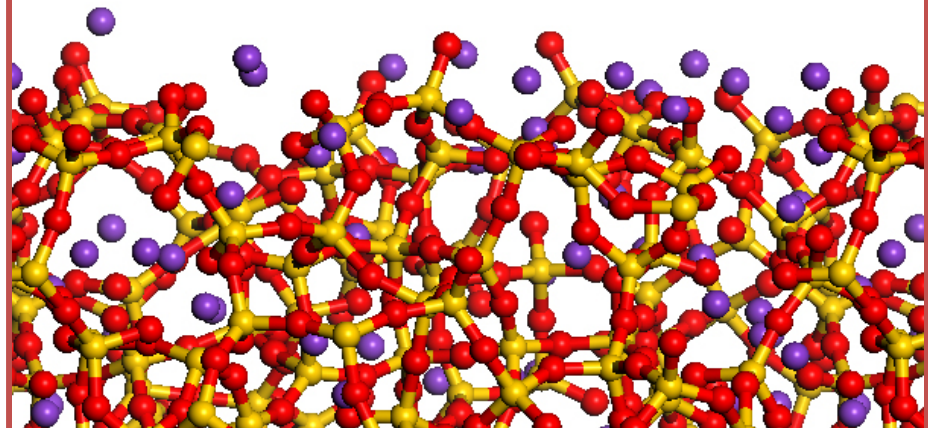
Relaxed silica fracture surface



Hydroxylated silica fracture surface

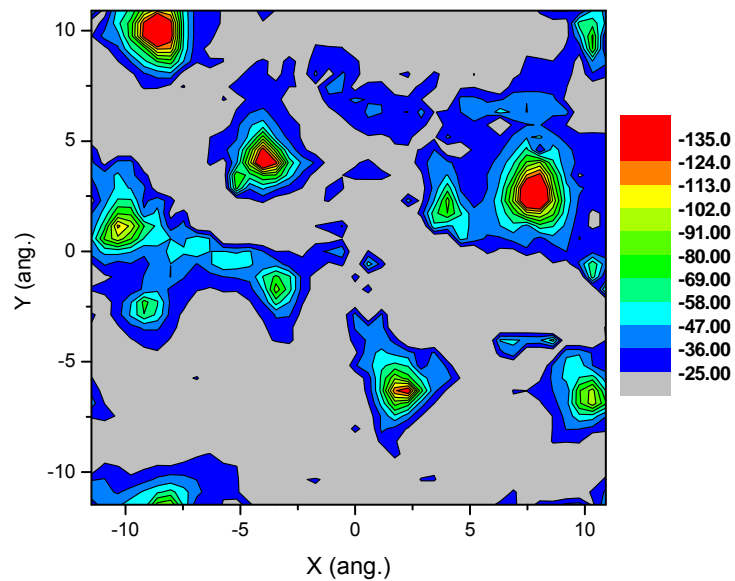


Relaxed sodium silicate fracture surface

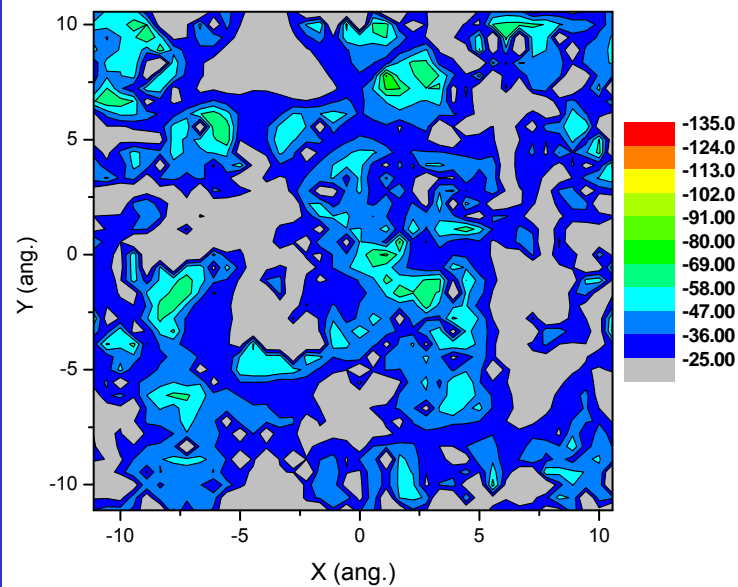


Silica

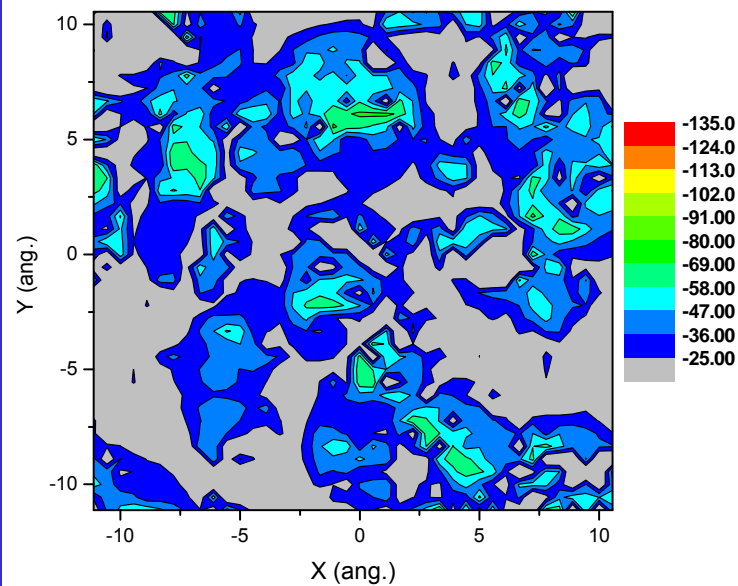
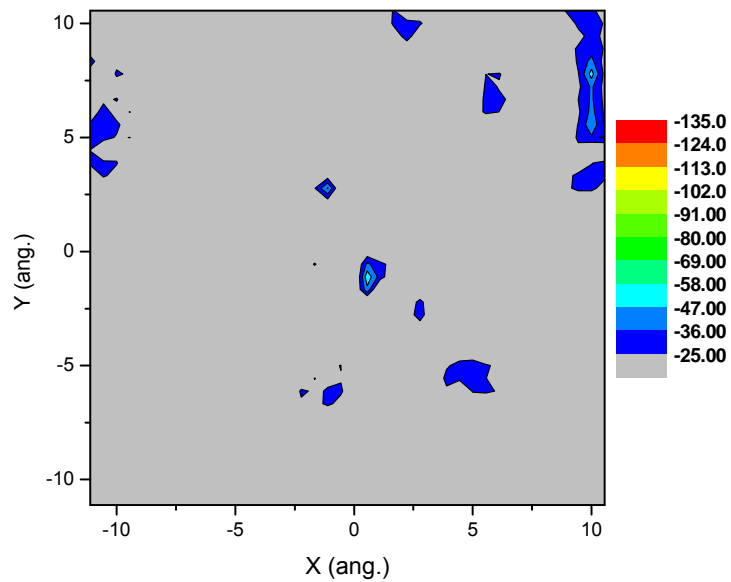
Fracture Surface



25 Na₂O – 75 SiO₂

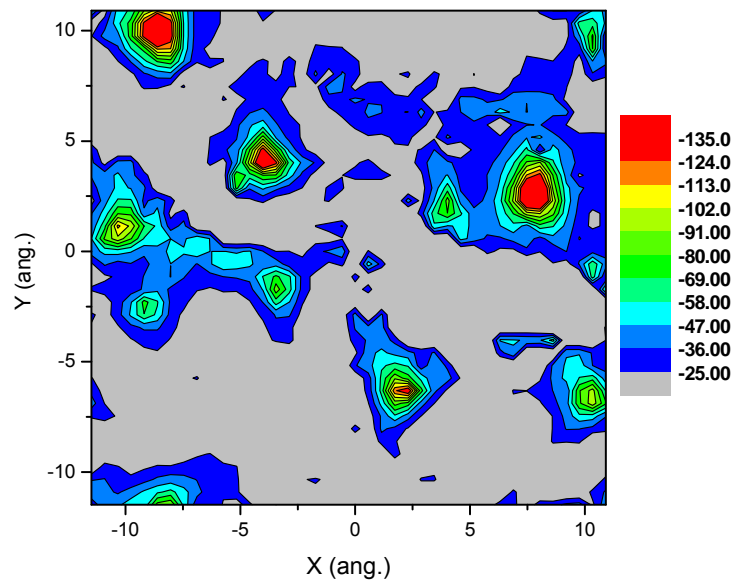


Melt Surface

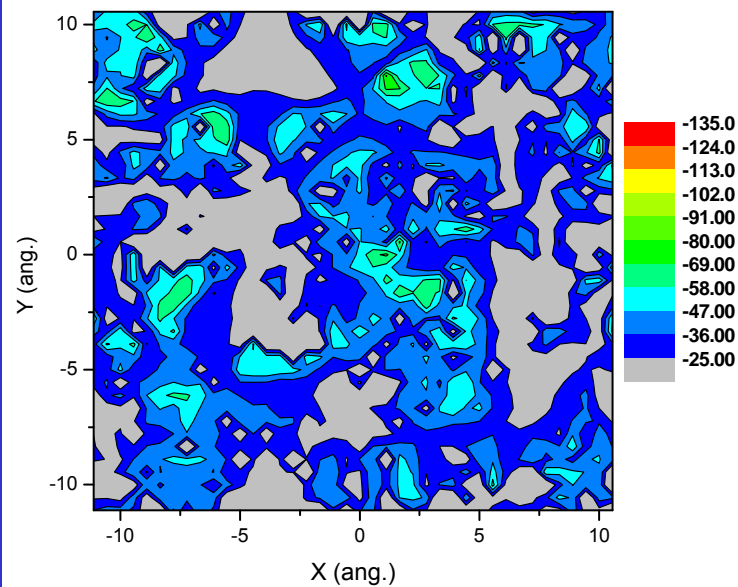


Silica

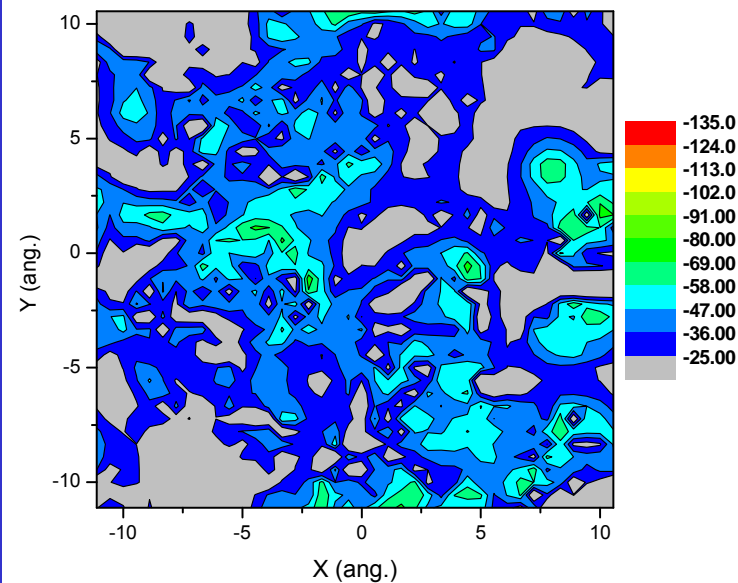
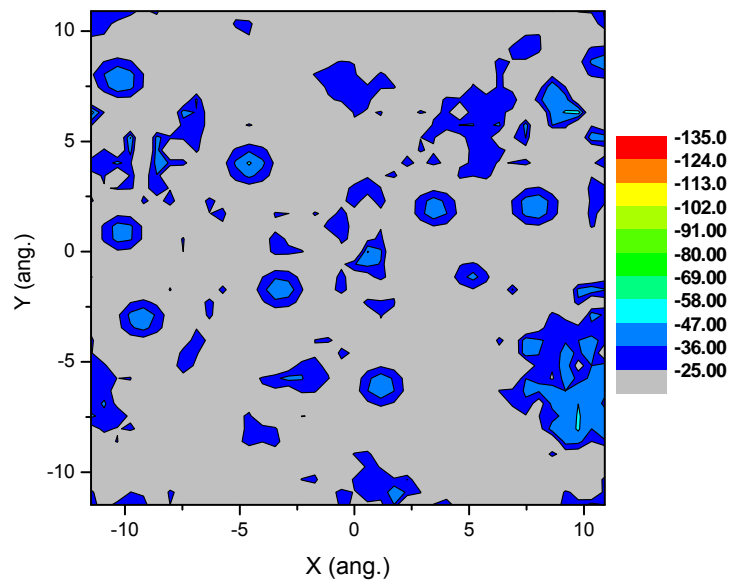
Fracture Surface



25 Na₂O – 75 SiO₂

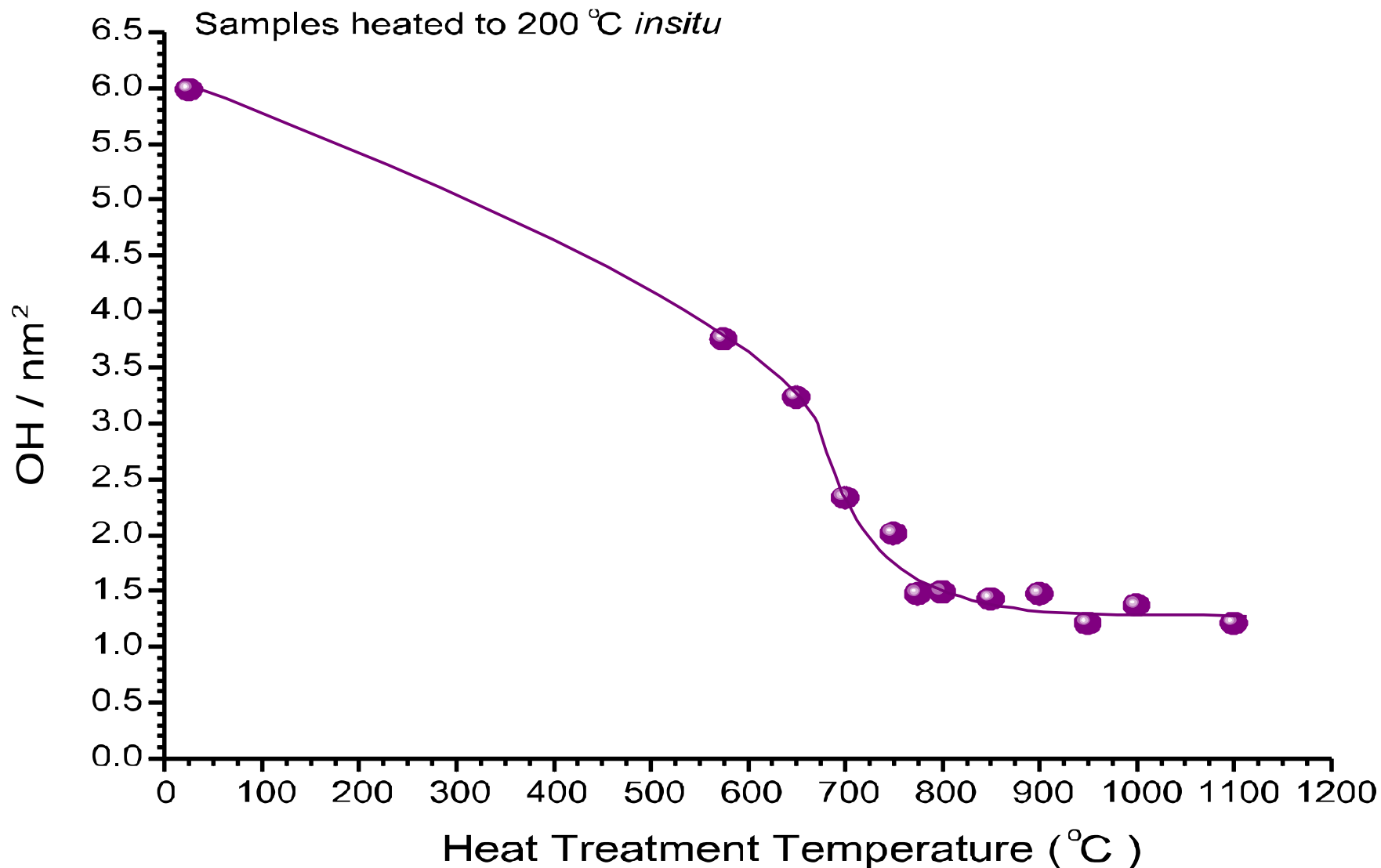


Hydroxylated FS

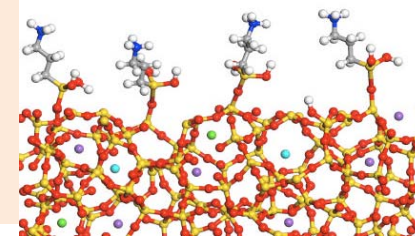




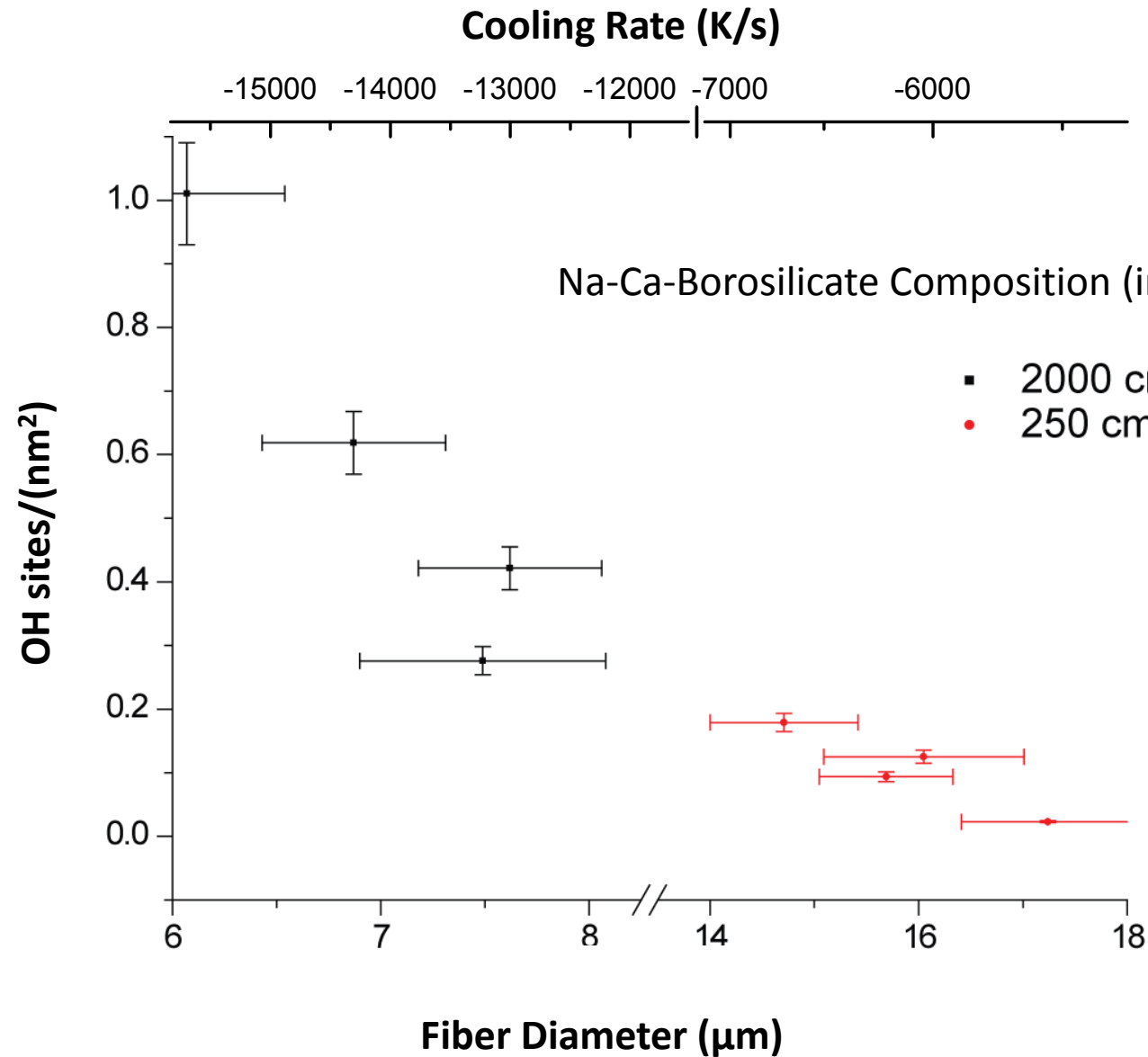
Dehydroxylation During Heat Treatment of SK6-Cleaned 1737GW



Surface Hydroxyl Concentration

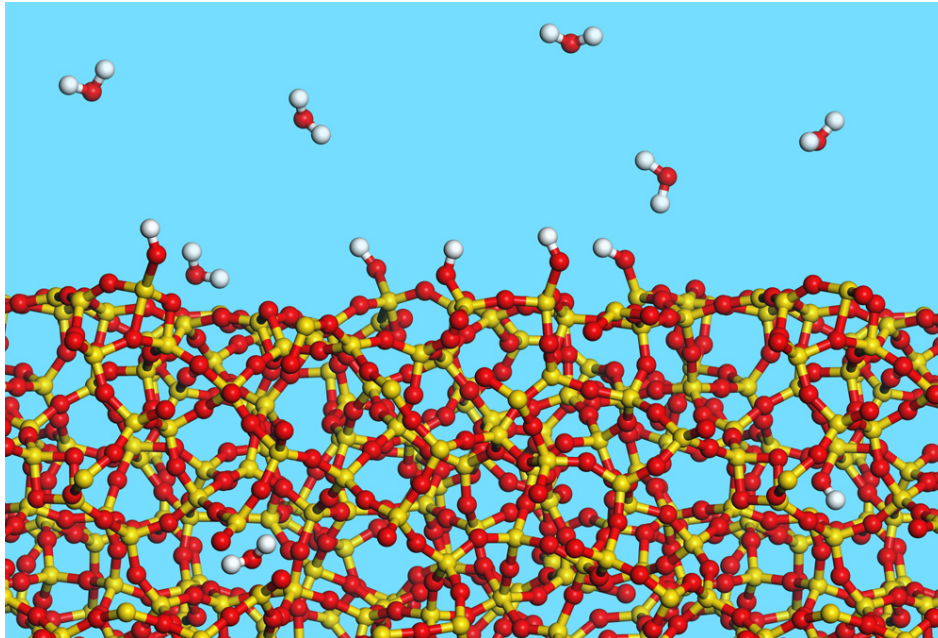


^{19}F MAS NMR

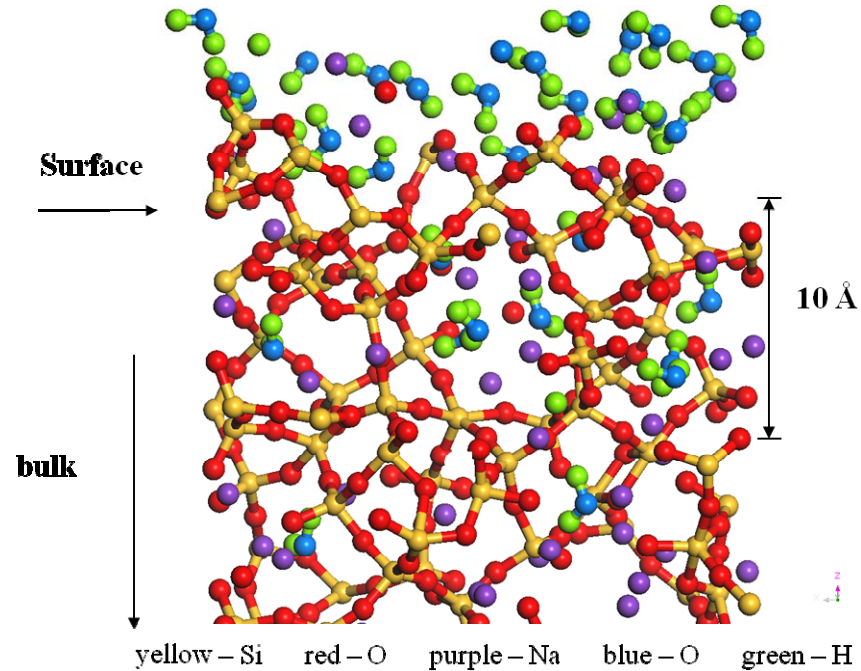


Inorganic Oxide Glass Surfaces

Silica (SiO_2) Glass



Multi-Component Silicate Glass



Surface Layer Formation

$\text{Na}^+, \text{Ca}^{++}, \text{Al}^{+++}$

- H_2O
 - H_3O^+
- by hydration and ion-exchange



The diagram illustrates the formation of a surface layer on glass. It features a rectangular frame containing two distinct regions. The upper region is labeled '(micro)porous silica-gel' and the lower region is labeled 'bulk glass'. A wavy horizontal line separates these two regions. Two orange arrows originate from the top of the frame: one points upwards towards the text ' $\text{Na}^+, \text{Ca}^{++}, \text{Al}^{+++}$ ' and the other points downwards towards the '(micro)porous silica-gel' layer.

(micro)porous silica-gel

bulk glass

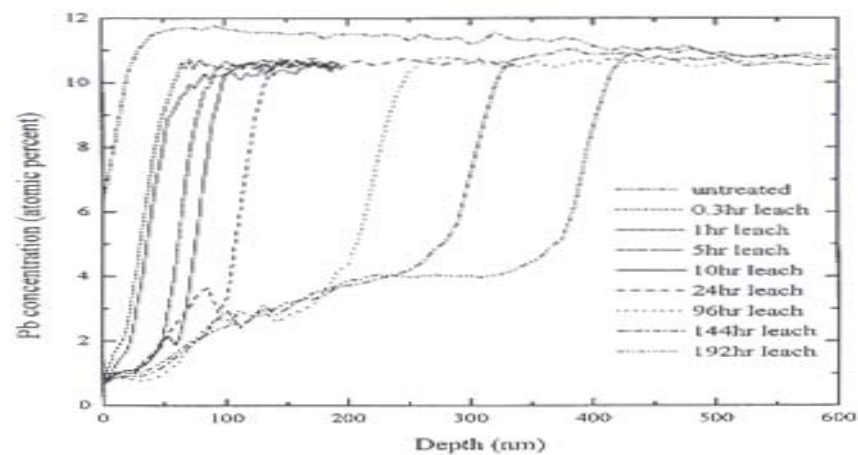
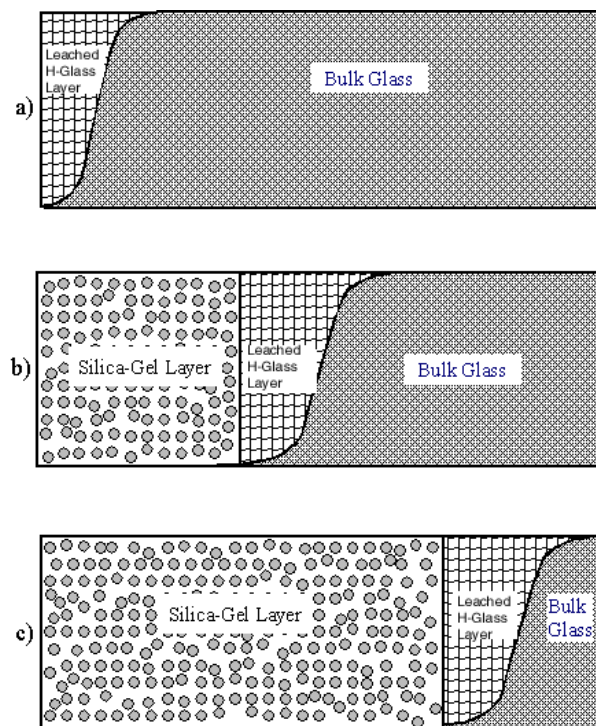
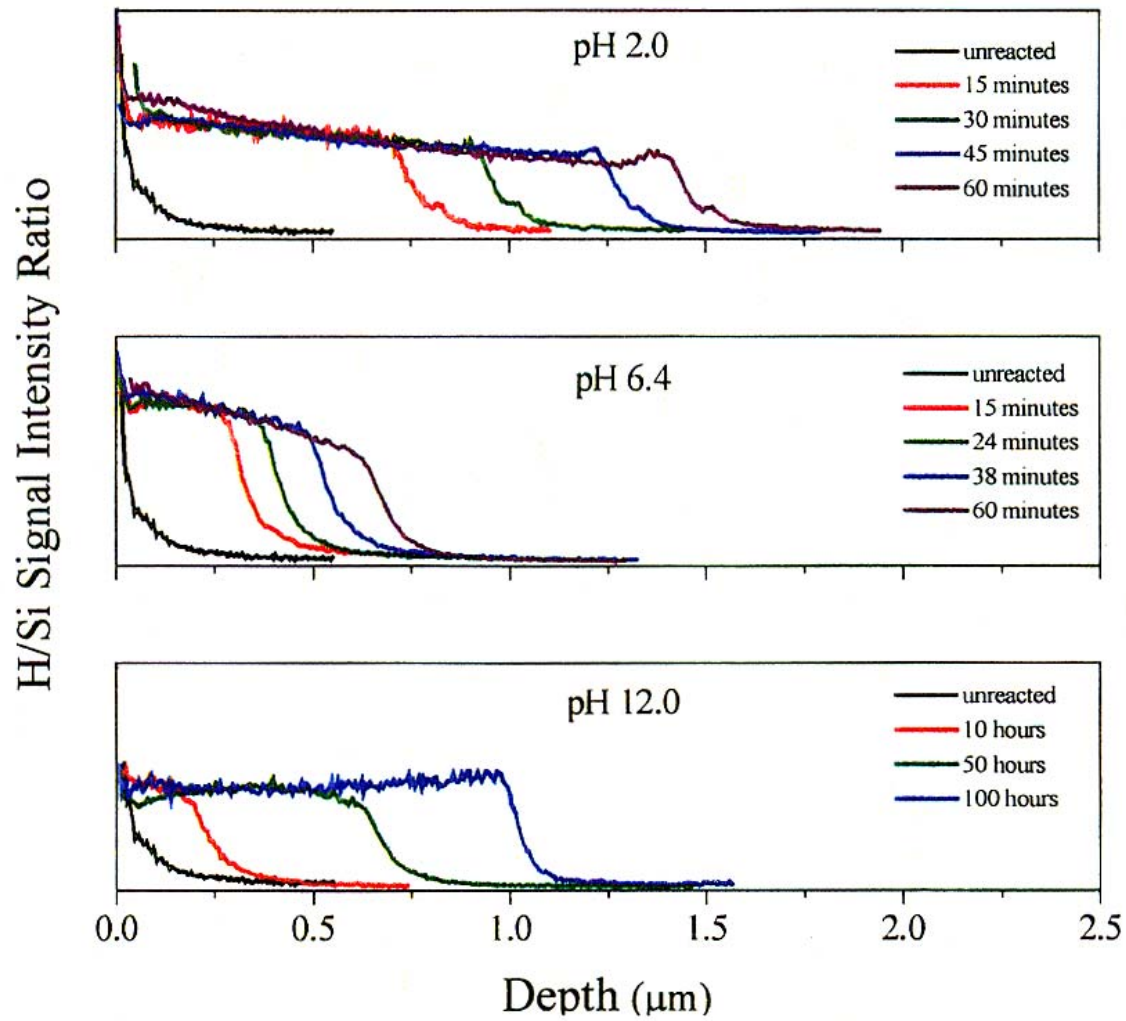


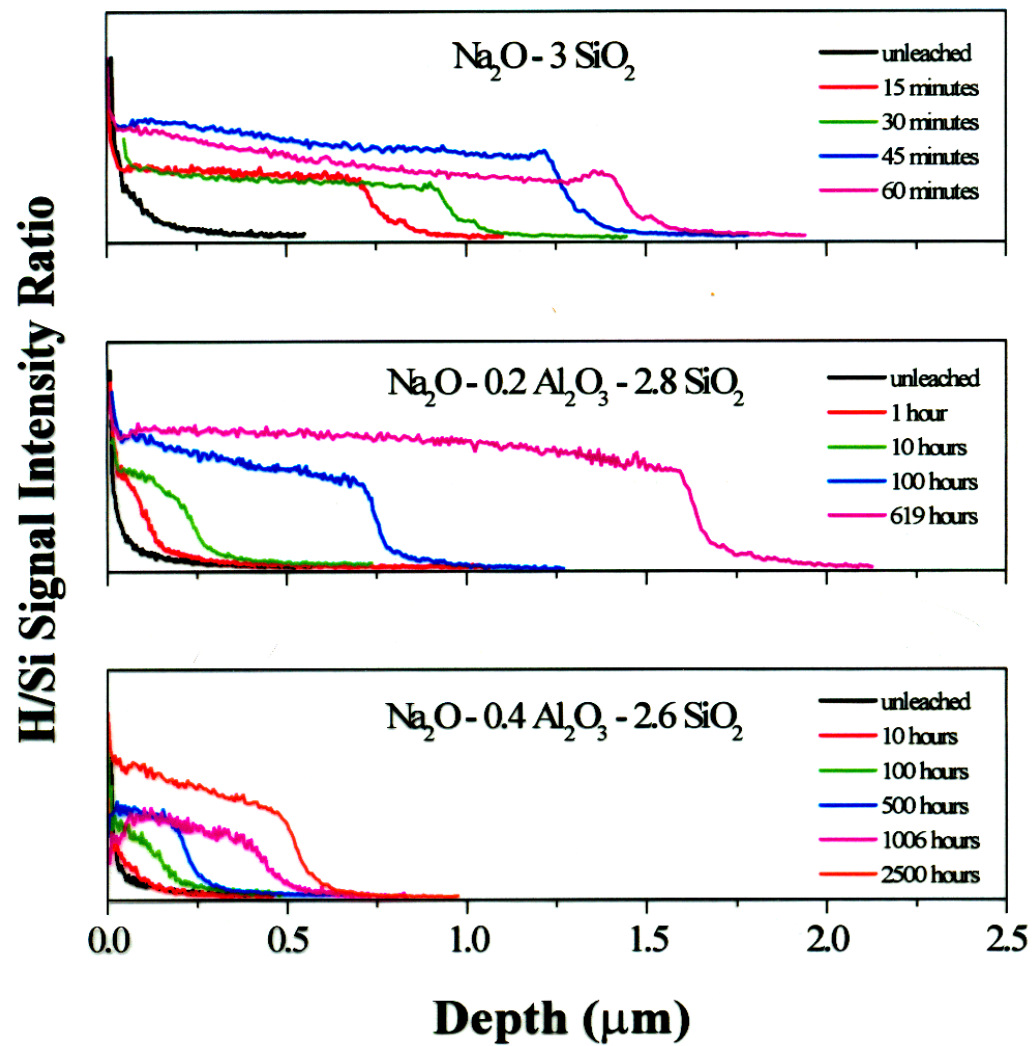
FIGURE 8. Lead depth profiles (obtained with SIMS) as a function of leaching time in 1N HCl



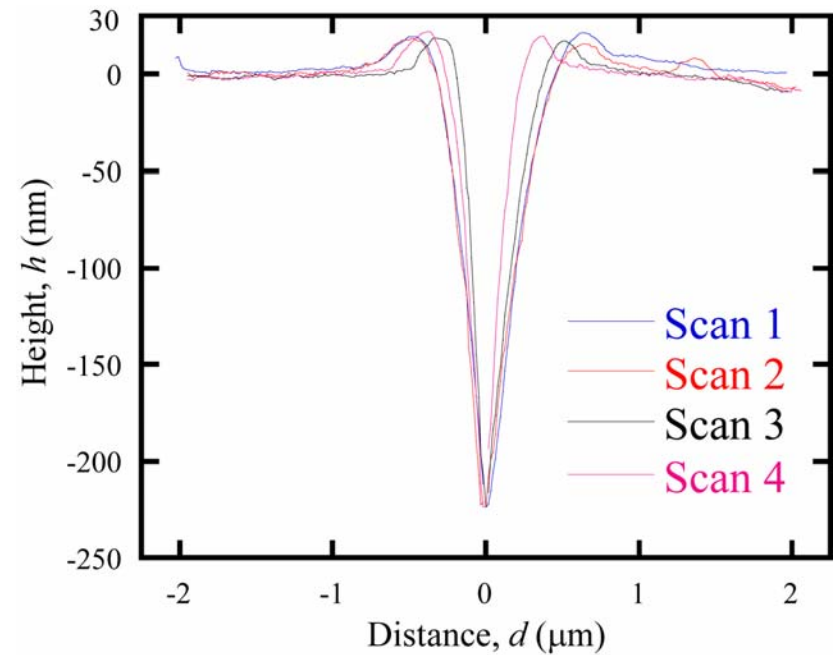
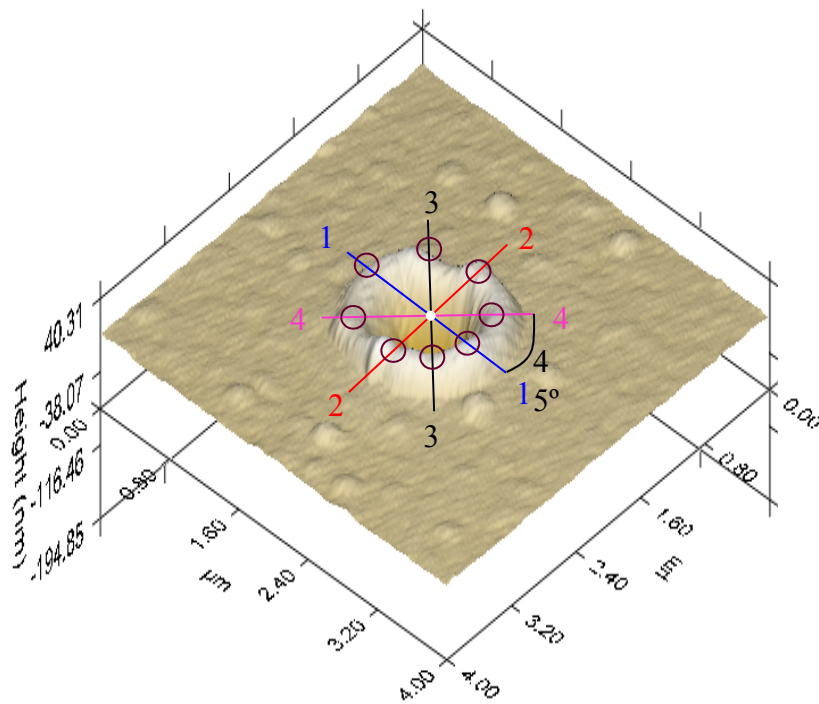
Sodium-Trisilicate Glass



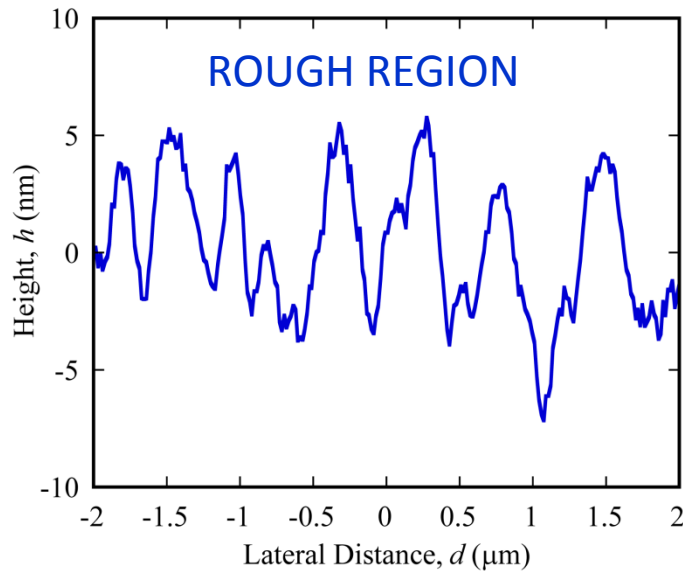
pH 2



Indentation Pile-up

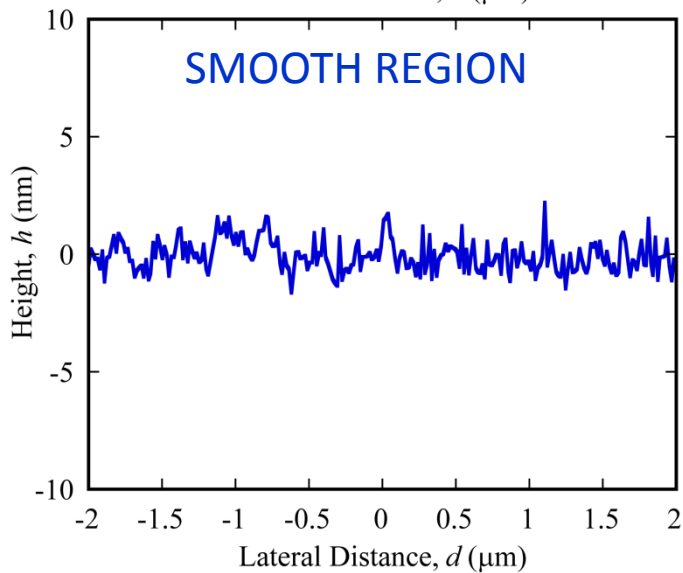
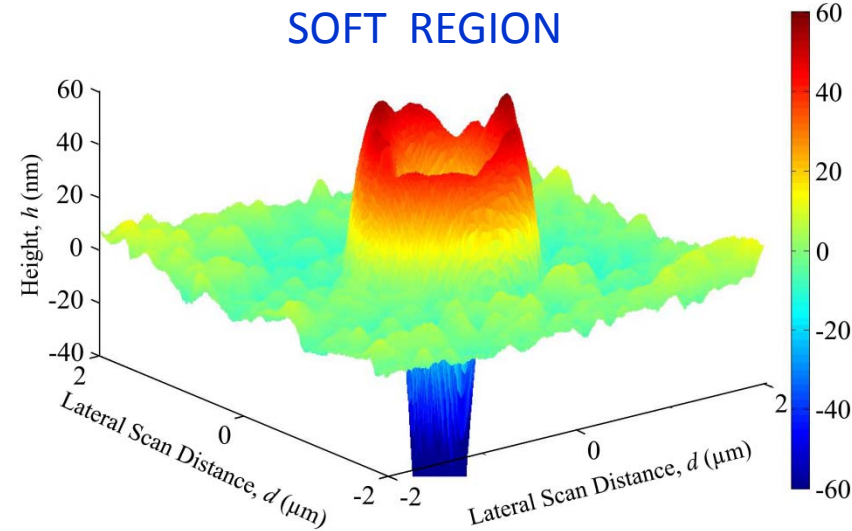


Soft and Hard Regions of Float Glass



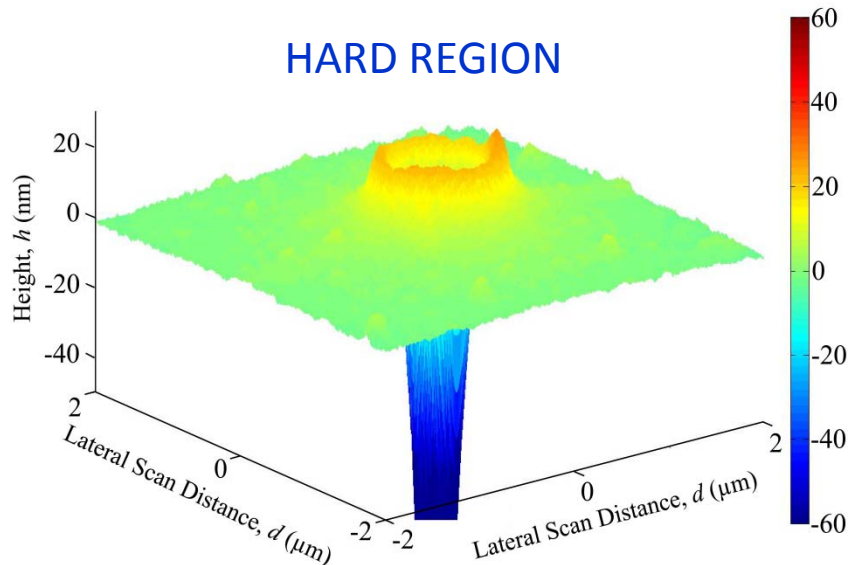
6500 μN

$$E_r = 72.0 \text{ GPa}$$
$$H = 7.34 \text{ GPa}$$



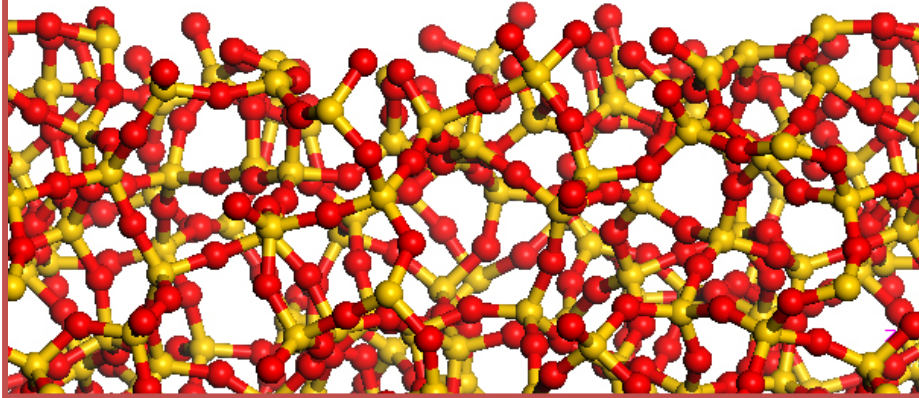
6500 μN

$$E_r = 78.0 \text{ GPa}$$
$$H = 8.16 \text{ GPa}$$

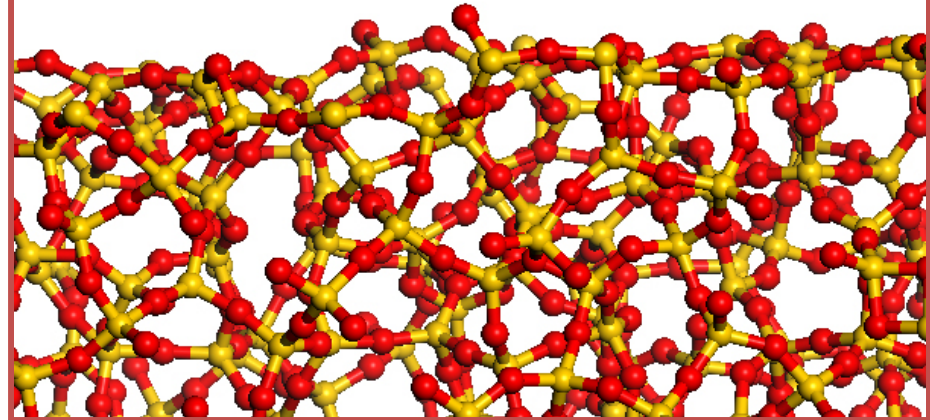


Glass Surface Structure Models

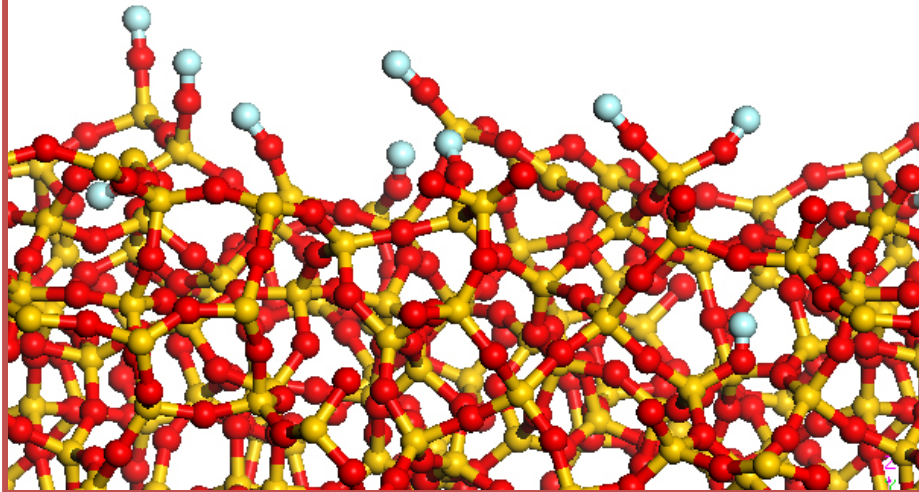
Silica at instant of fracture



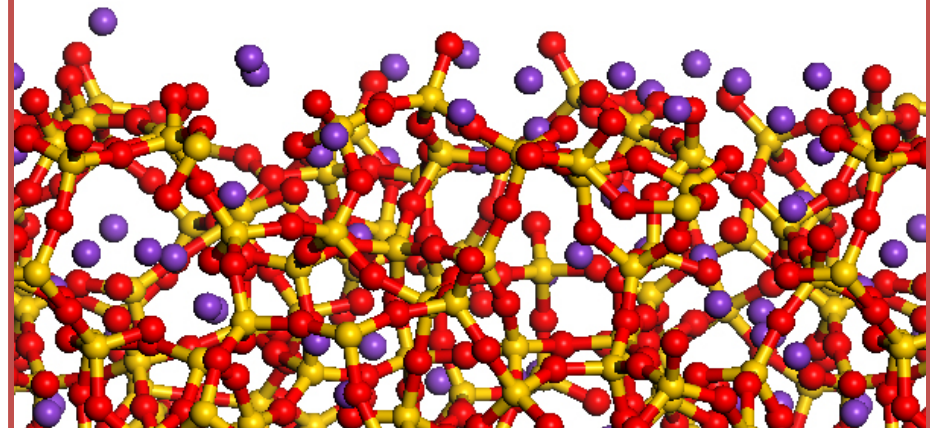
Relaxed silica fracture surface



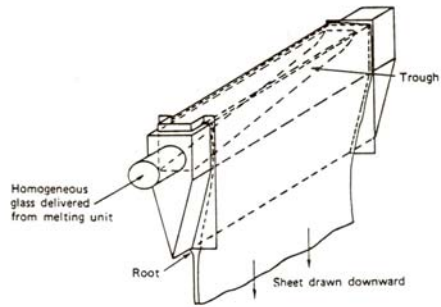
Hydroxylated silica fracture surface



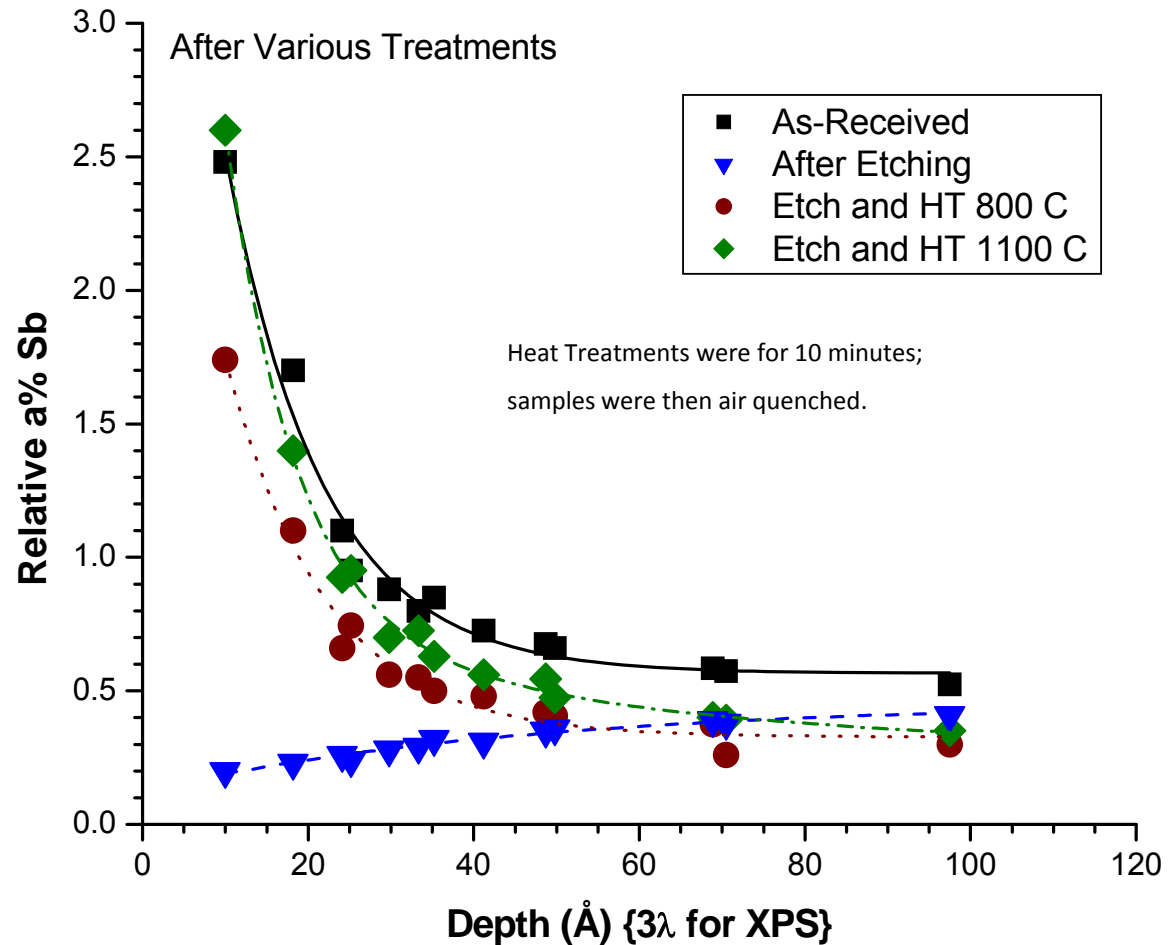
Relaxed sodium silicate fracture surface

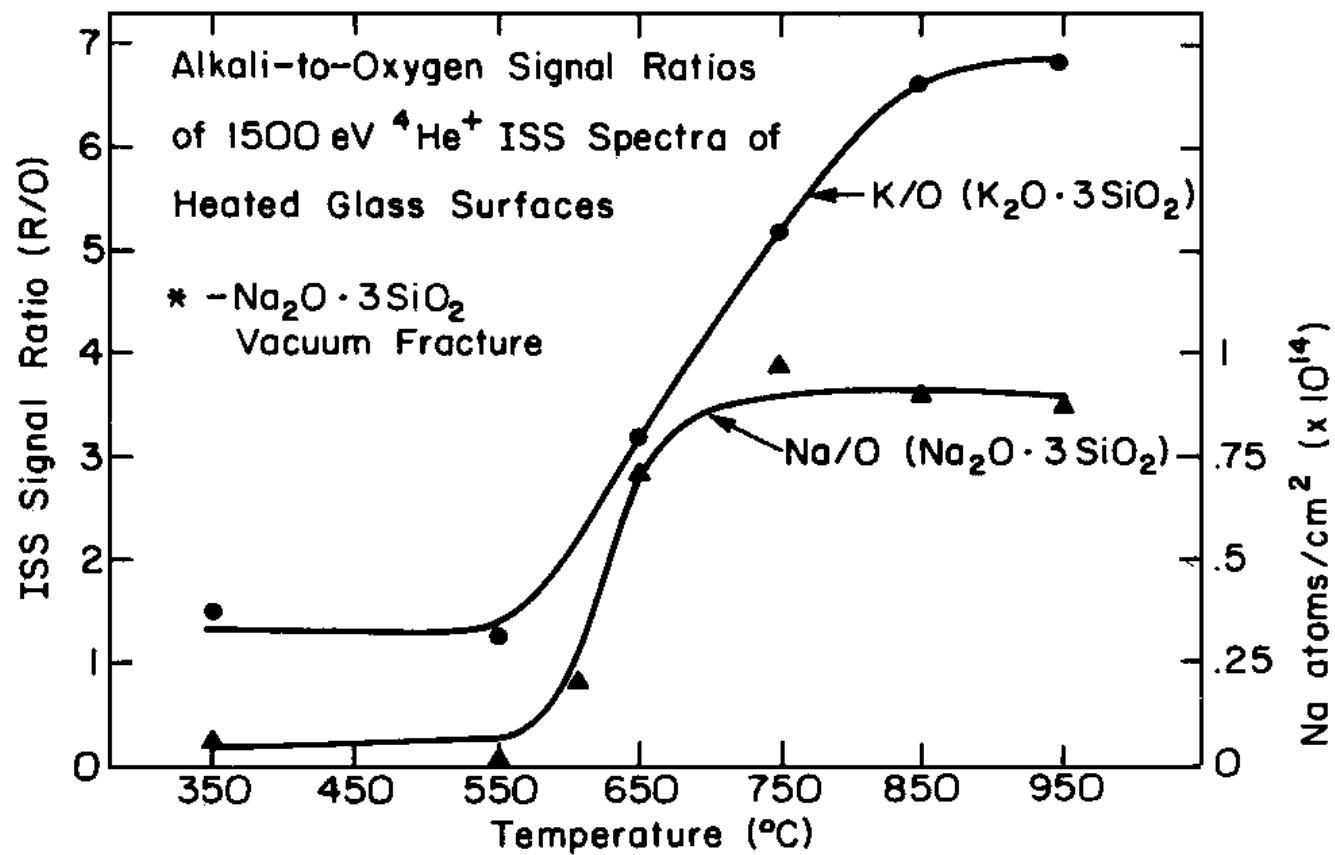


Antimony Depth Distribution by Angle-Resolved XPS and FAB-Static SIMS

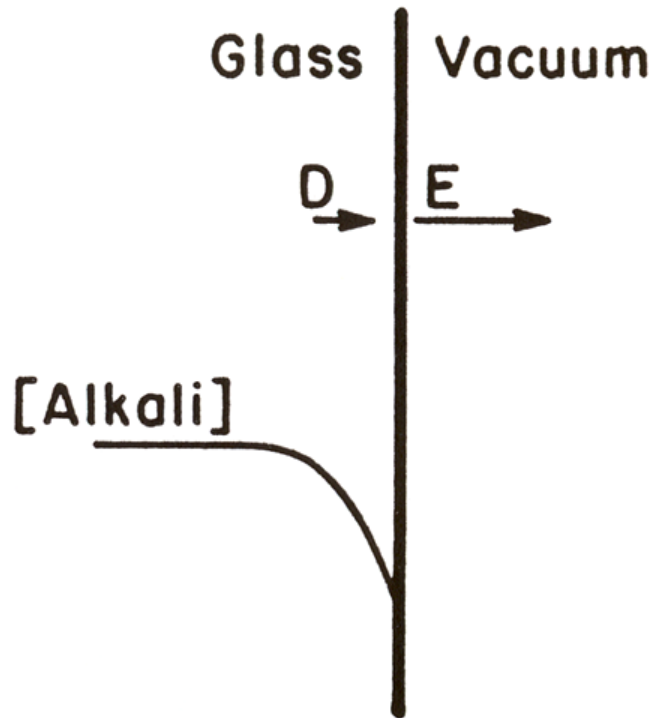


**Alkaline-Earth
Boroaluminosilicate
Display Glass**

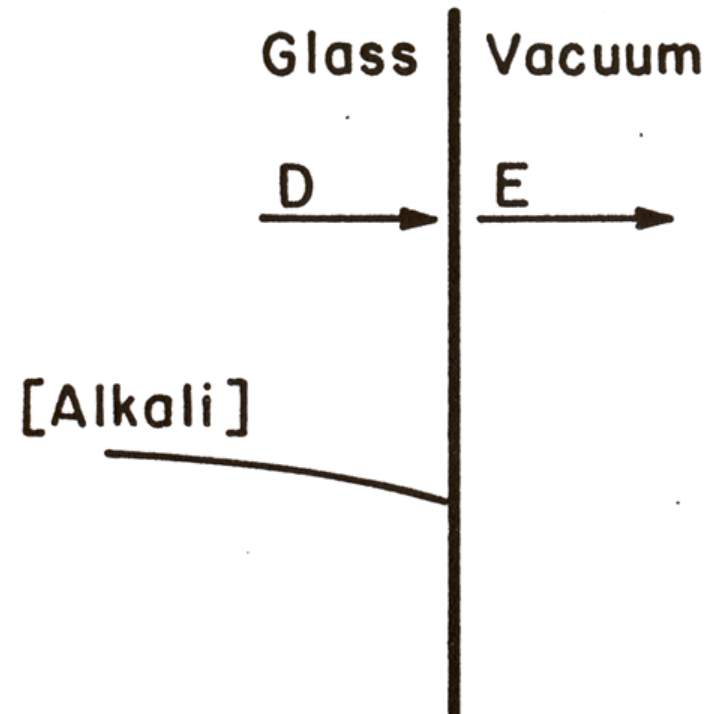




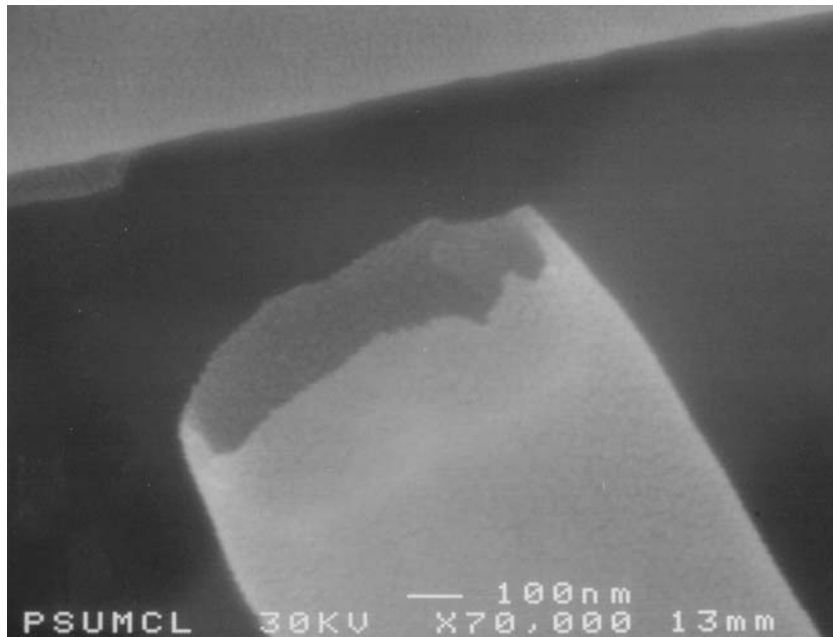
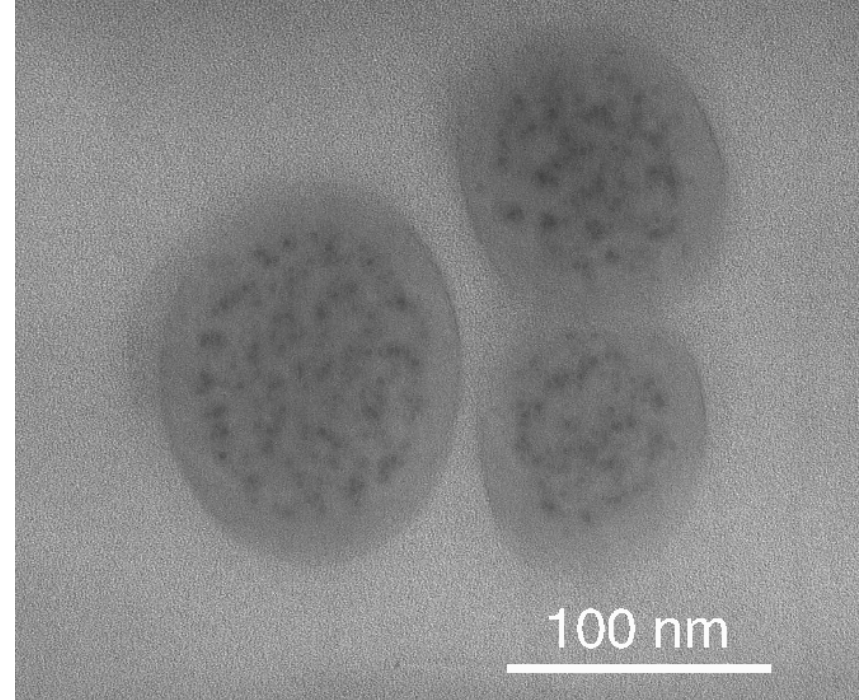
Low Temperature



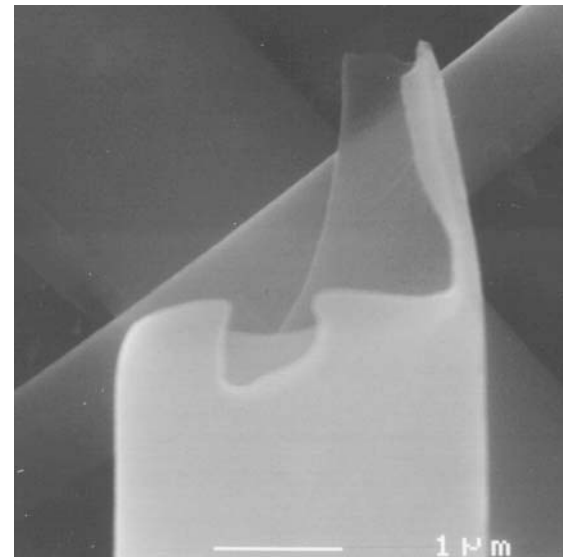
High Temperature



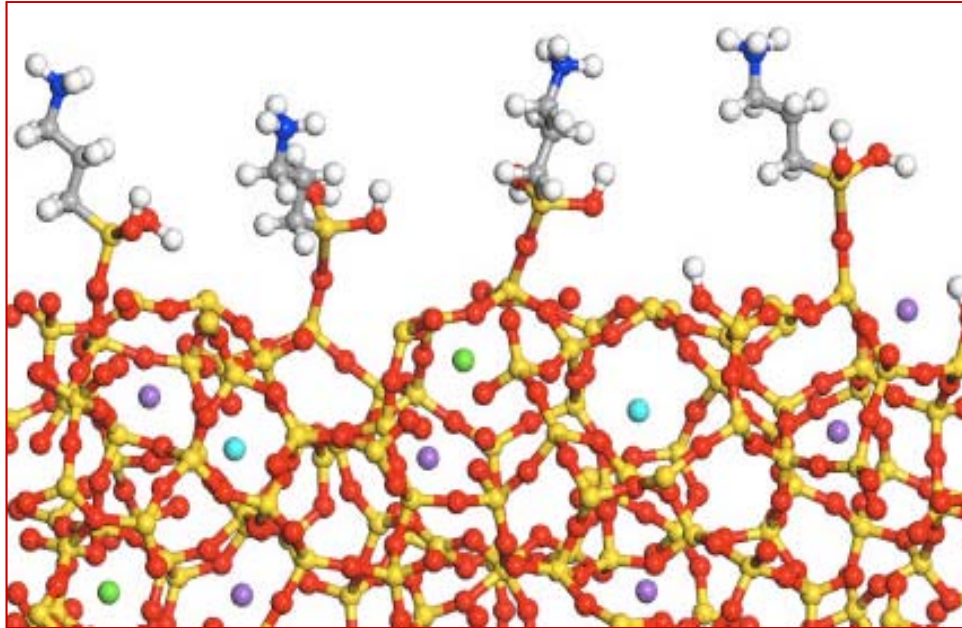
Fiber Surface Layer by TEM and SEM



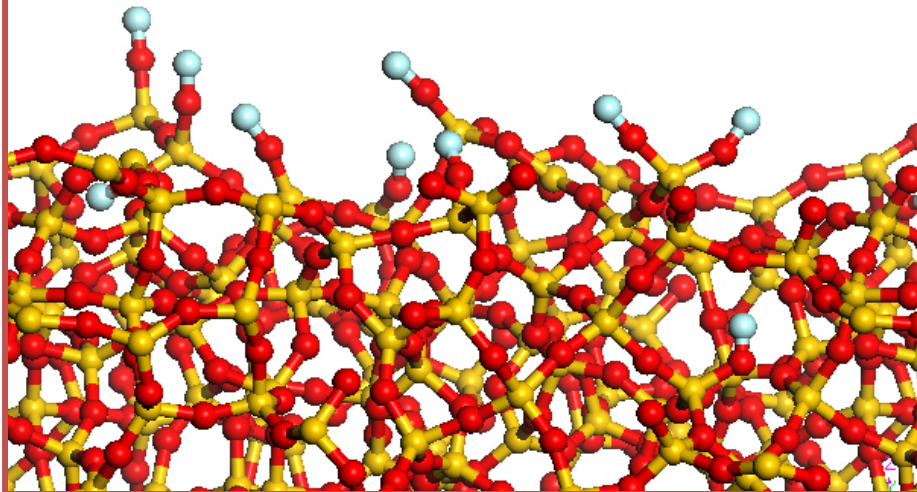
FA fiber corroded by
simulated body fluid



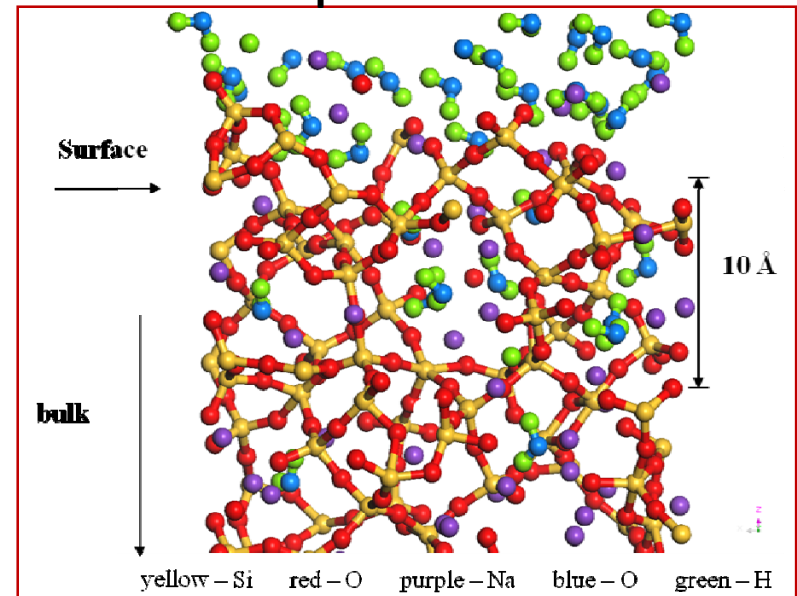
Organo-Functionalization of Glass Surfaces



Hydroxylated Silica Surface



Multi-Component Glass Surface



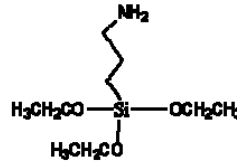
“chemical” water barriers ?

coupling
agents

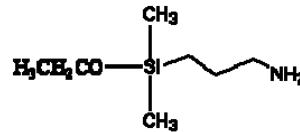
Silanes

hydrophobic

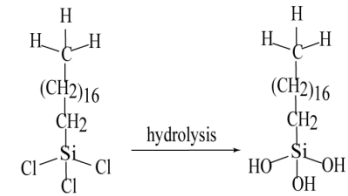
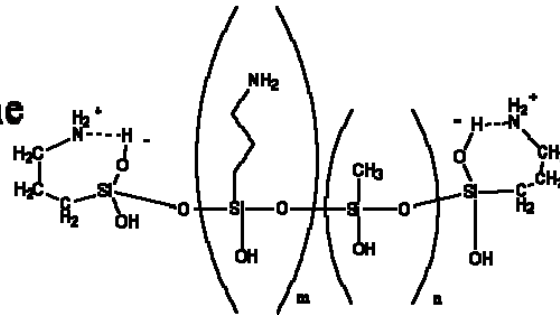
- **γ -aminopropyltriethoxysilane**
(trifunctional)



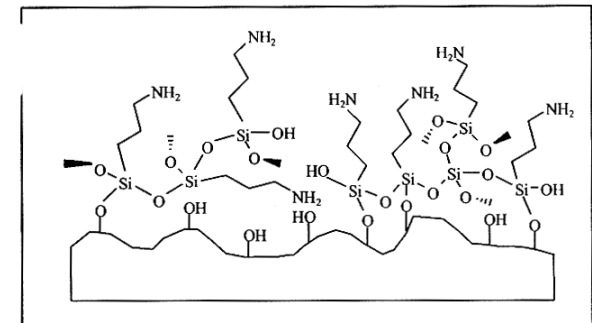
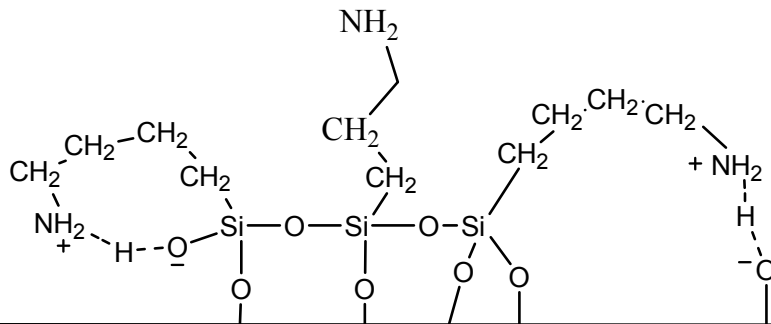
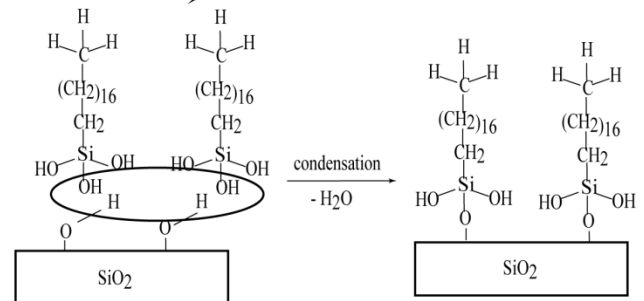
- **3-aminopropyldimethylethoxysilane**
(monofunctional)



- **Aminoalkylsilsesquioxane**
(oligopolymeric)



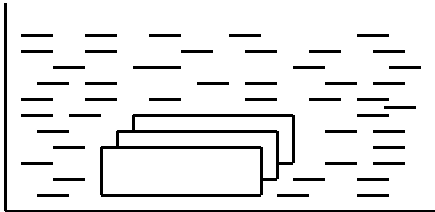
adsorption



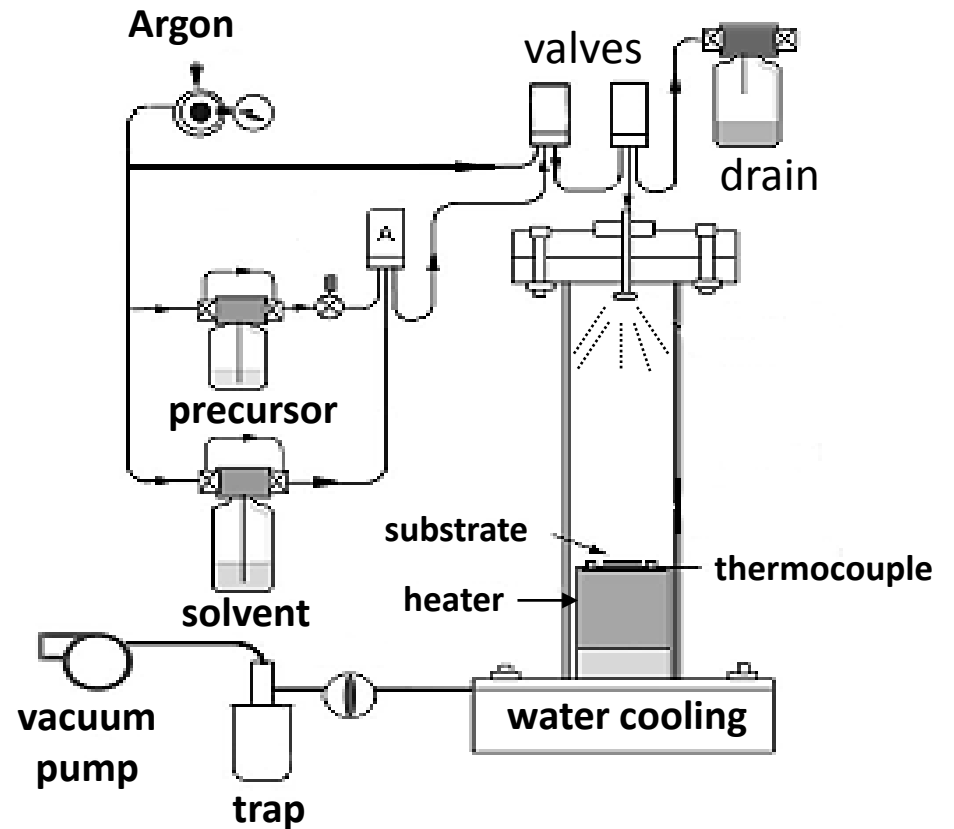
Scheme 2.5: Schematic representation of the APS multilayer obtained by Method 2, the gasphase silanization procedure of Haller [20].

Silanization process:

Dipping

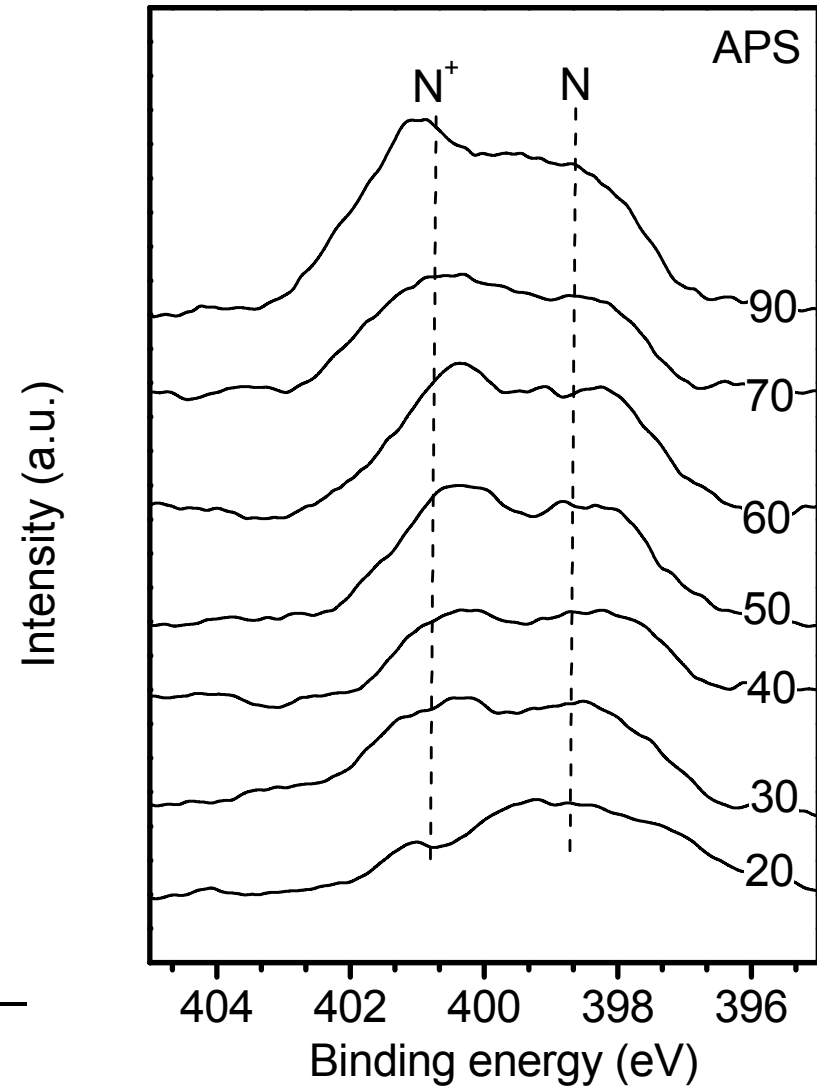
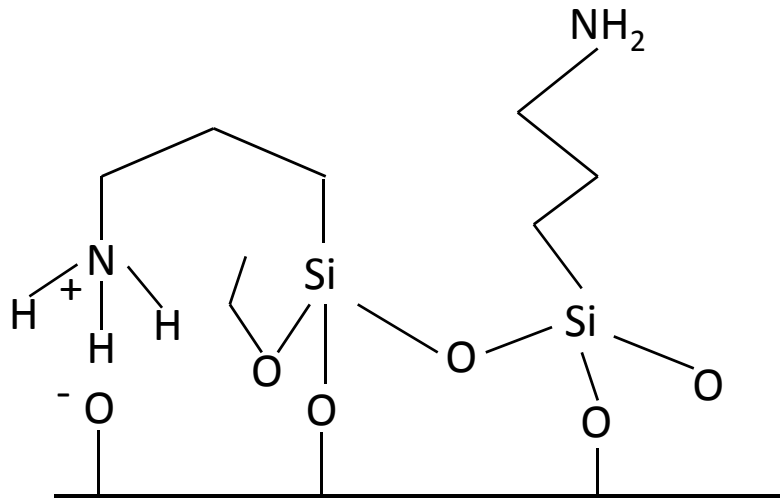


CVD



Angle dependent XPS results

A preference for the protonated amine to be oriented towards the glass surface and the non-protonated ones to be oriented away from the surface is suggested.



Composite fracture surface: azide functional silane on silica beads in polyethylene

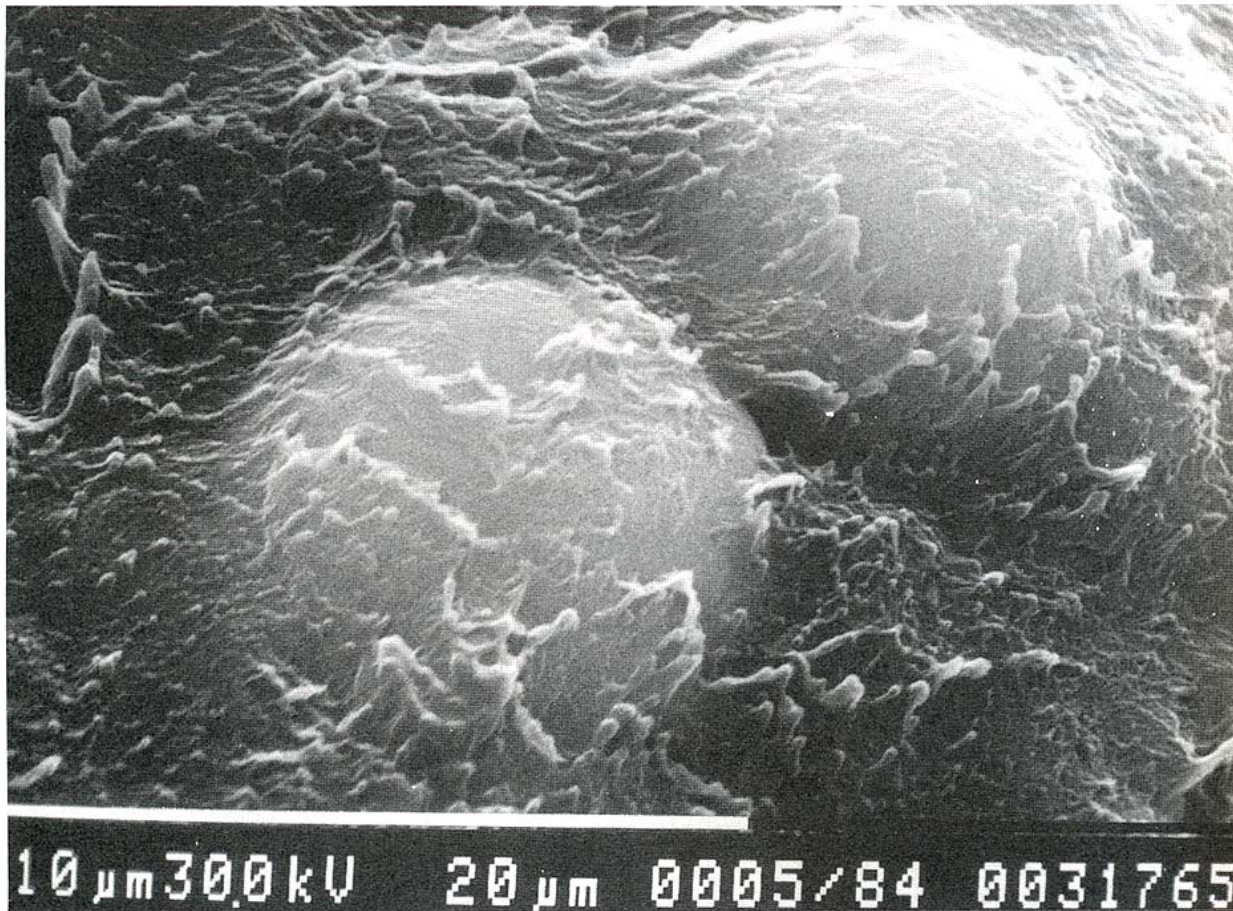
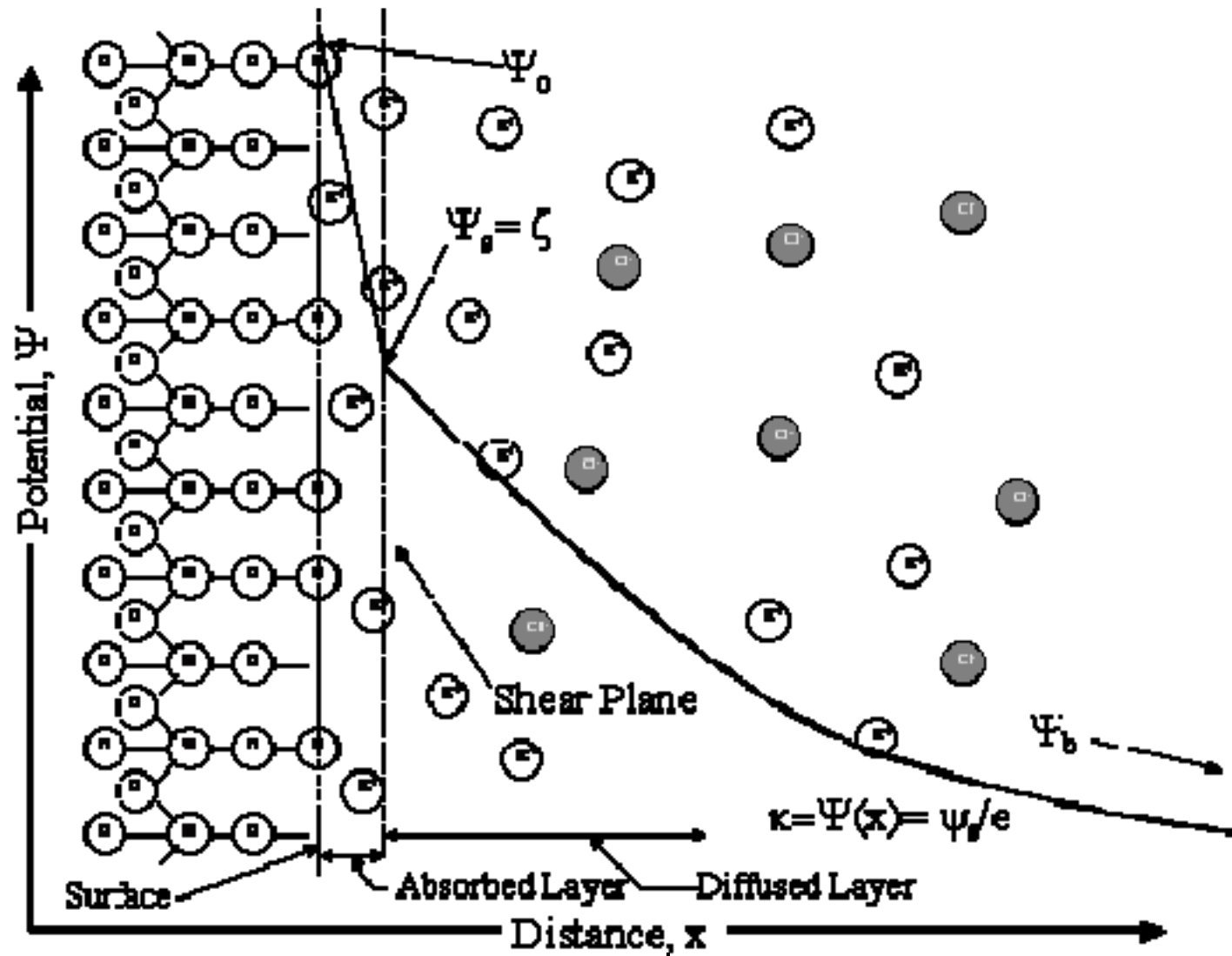
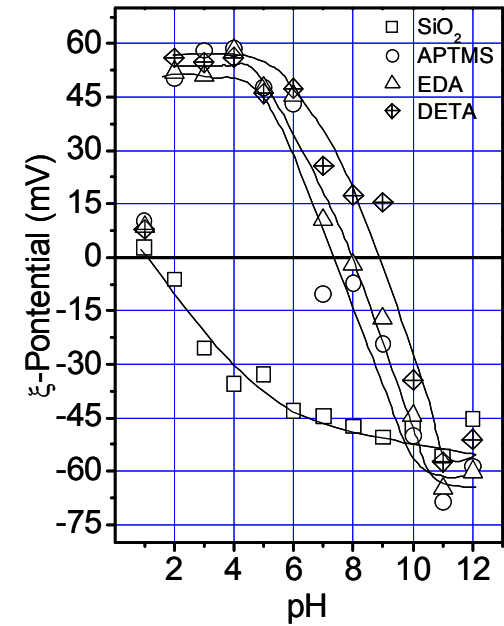
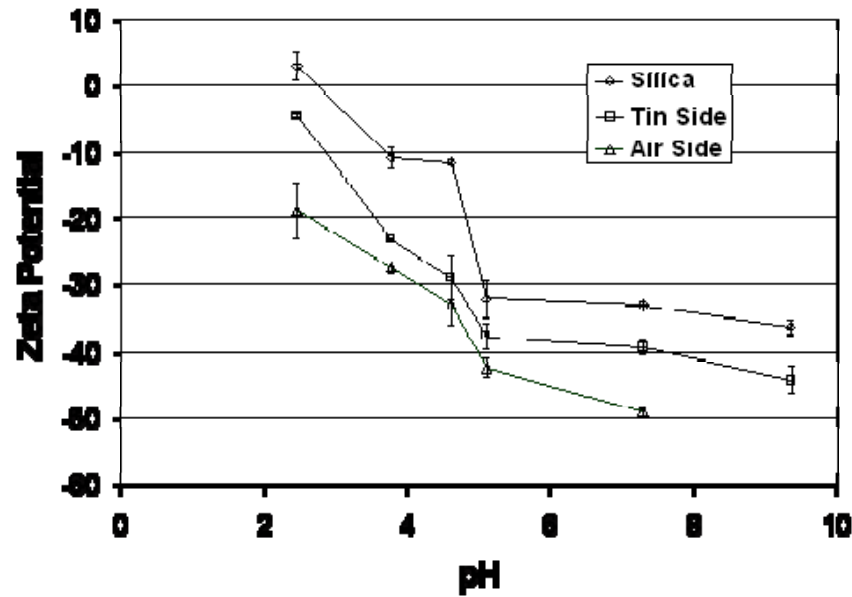
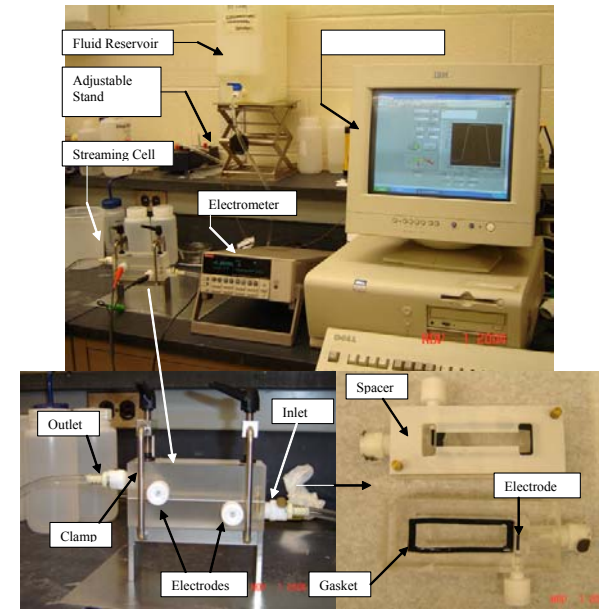
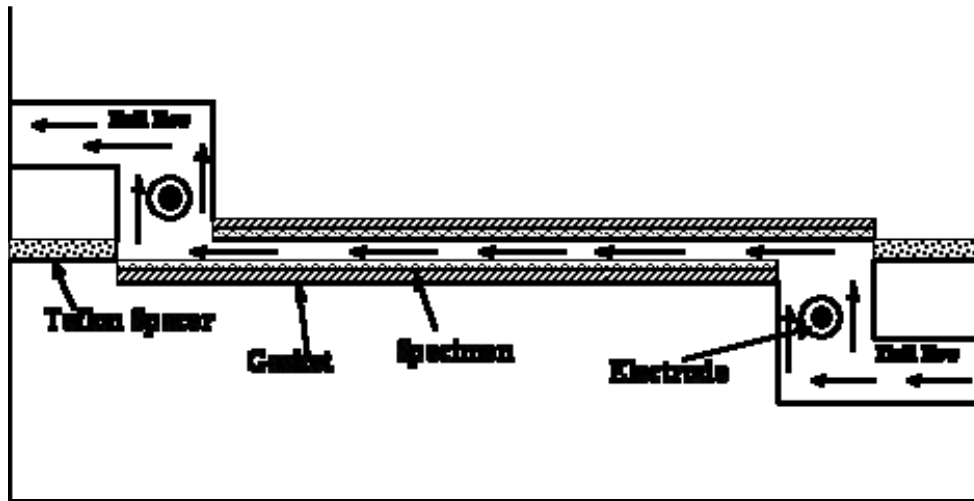


FIGURE 5. Scanning electron micrograph of the fracture surface of a glass-sphere-filled high-density polyethylene where the glass has been modified with an azide-functional silane.

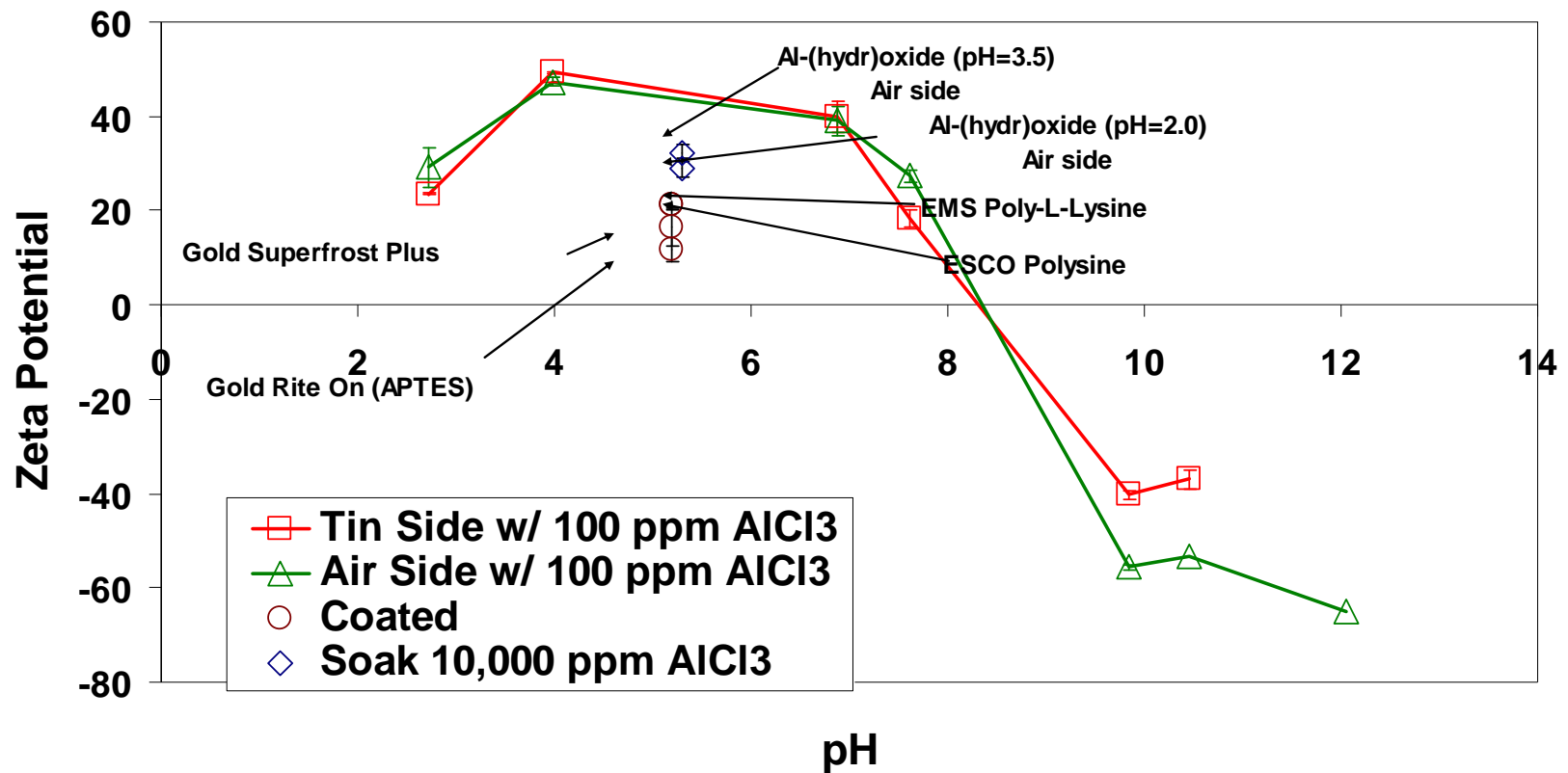
Electrical double layer at the glass-water interface



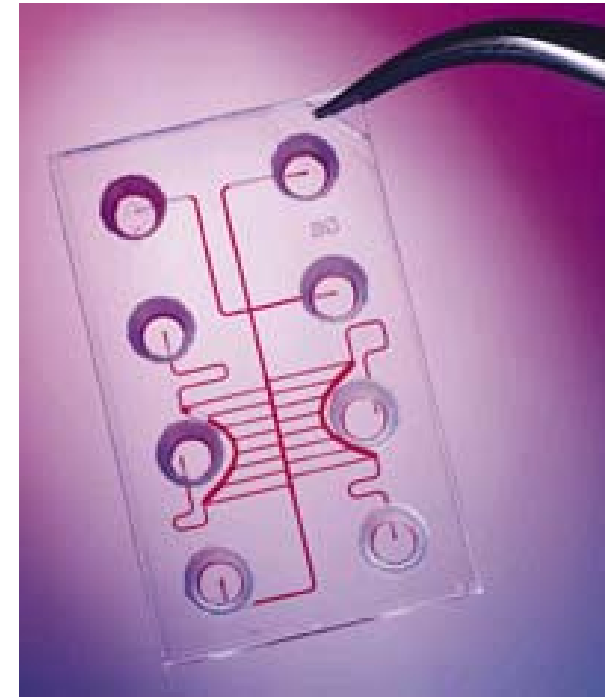
Characterizing surface charge by streaming potential



Glass surface modification using inorganic and organic coatings

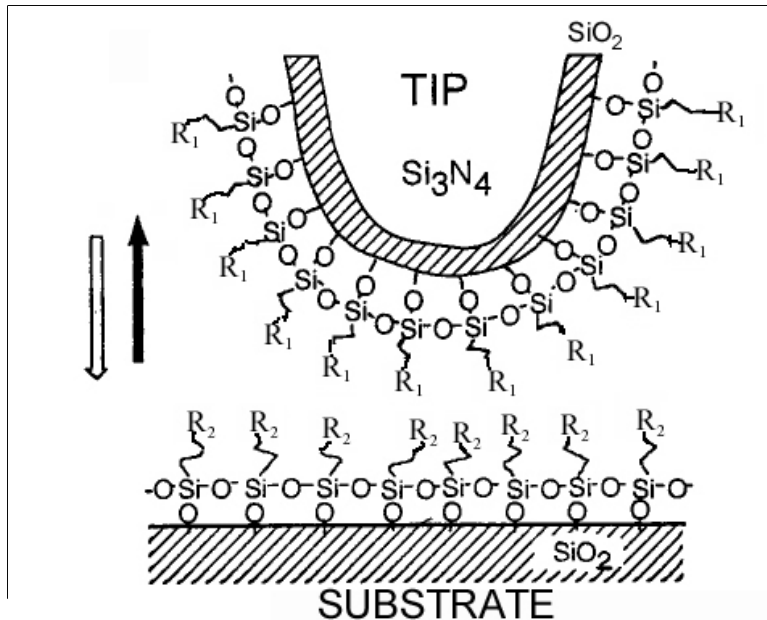


Glass Surfaces and Coatings for Biotechnology

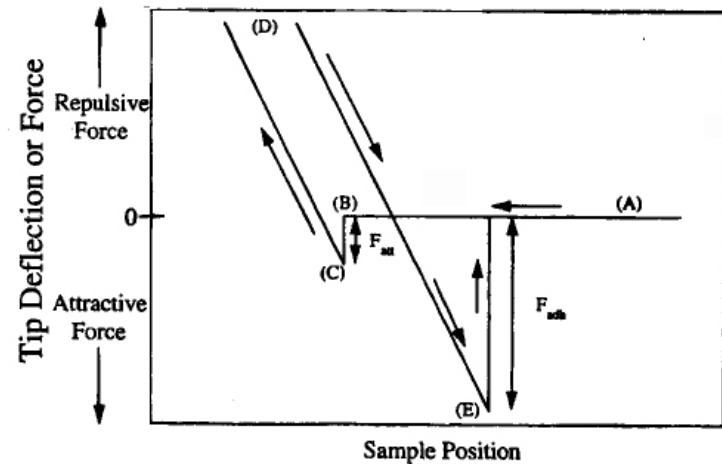


Adhesive Force Studies by Chemical Force Microscopy (CFM)

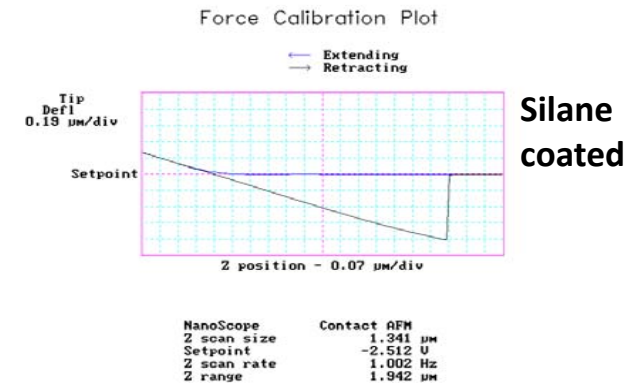
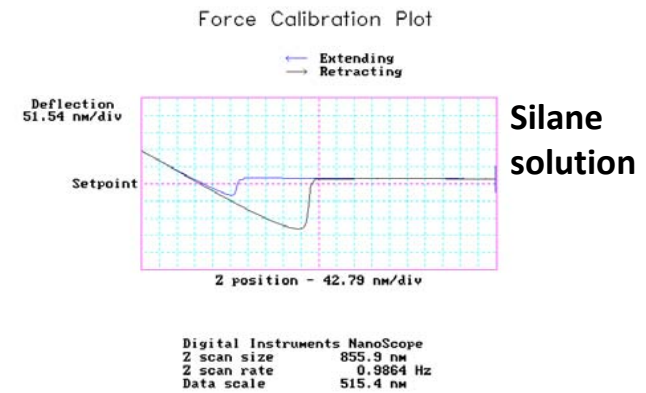
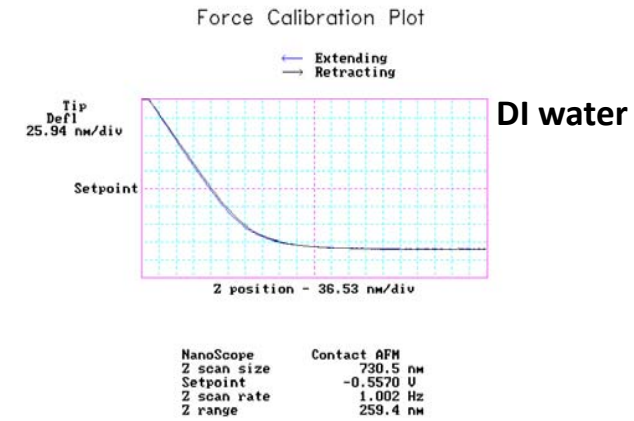
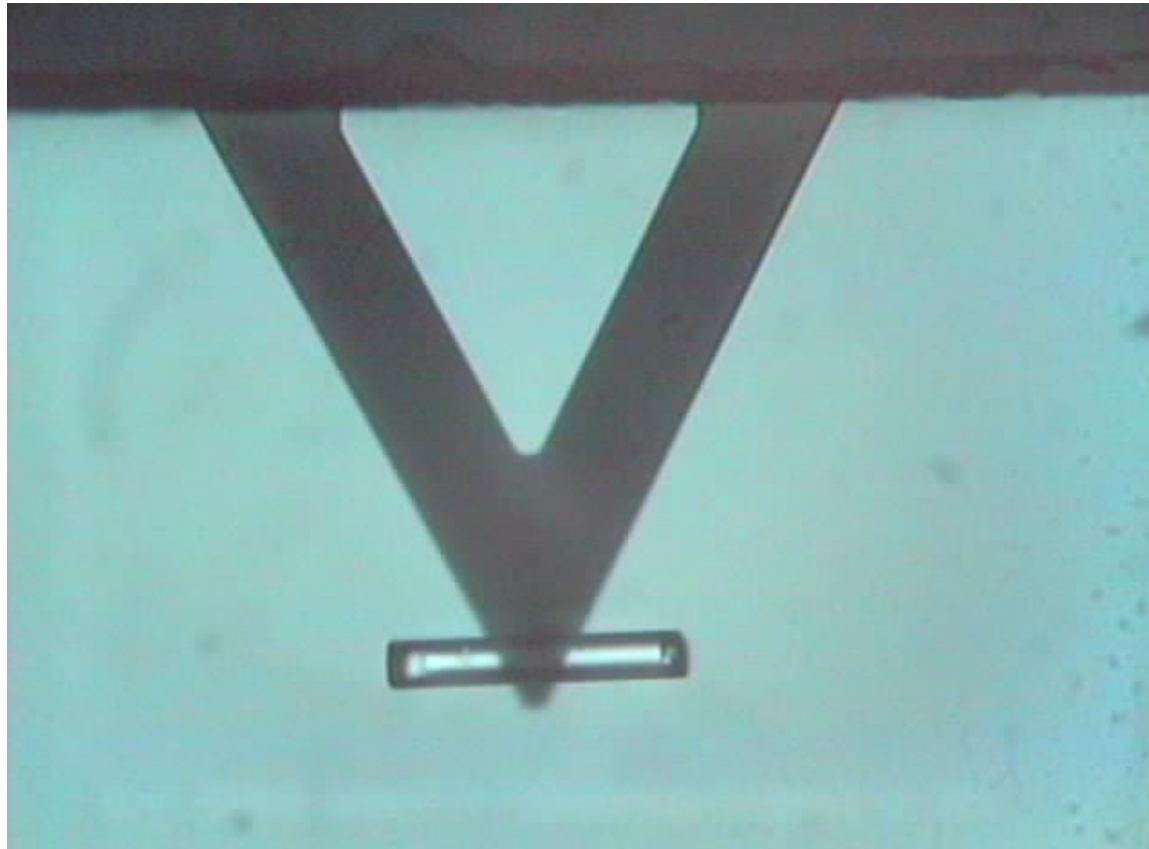
Functionalized Si_3N_4 Tip



Force-Distance Measurements



fiber probe for AFM/CFM (glass fiber diameter 10 μm)



THE PENNSYLVANIA STATE UNIVERSITY



Interdisciplinary Materials Research, Science and Engineering at Penn State

Core Competencies:

- nanoscience, nanomaterials and nanostructures
- electronic materials, devices and systems
- functional polymers and ceramics
- synthesis, processing and manufacture
- materials characterization and surface science
- computational modeling and simulation

Glass Research at Penn State

Faculty:

- David Green (mechanical)
- John Hellman (struct/proppants)
- Seong Kim (polymer coatings)
- Mike Lanagan (dielectric props)
- Karl Mueller (NMR/surface chem)
- Chris Muhlstein (nanomechanics)
- Carlo Pantano (surfaces/coatings)

Opportunities:

- Coatings: processing and properties
- Mechanical properties and strength
- Corrosion and weathering
- Glass for capacitors
- Microwave processing

- High performance buildings
- Solar for pv and fuel
- Composites

the Art and Science of Glass



Outline

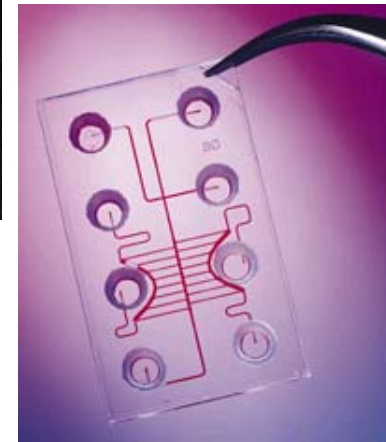
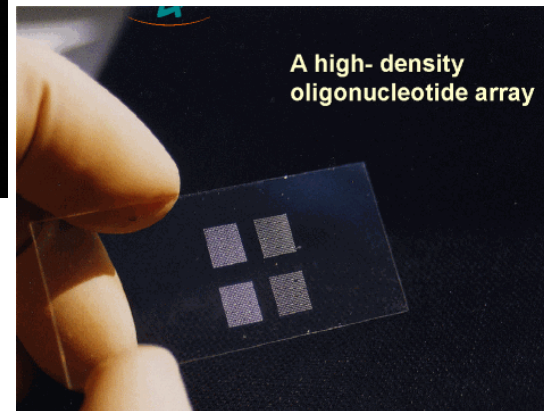
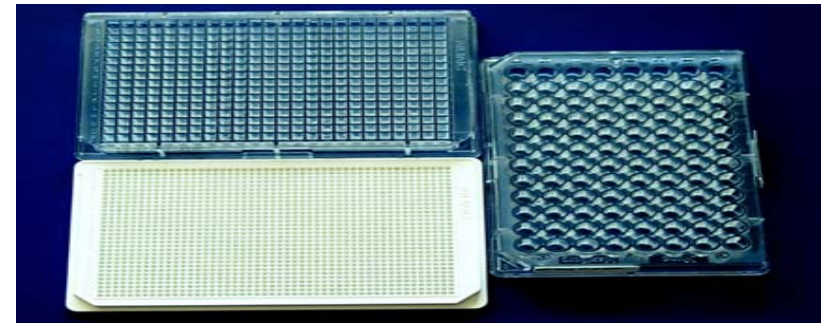
Part 1: Fundamentals

- **Surface Structure and Adsorption**
 - fracture surface vs melt surface
 - silica vs multicomponent
- **Surface and In-Depth Reactions**
- **Surface Functionalization**

Part 2: Functional Surfaces

- **DNA Microarray Substrates**
- **Semiconducting Glass Surfaces**
- **Nanoscale Carbon Coatings**
- **Glass-Polymer Interfaces**

Glass Surfaces and Coatings for Biotechnology





Glass slides to DNA microarrays

by Samuel D. Conzone* and Carlo G. Pantano†

A tremendous interest in deoxyribonucleic acid (DNA) characterization tools was spurred by the mapping and sequencing of the human genome. New tools were needed, beginning in the early 1990s, to cope with the unprecedented amount of genomic information that was being discovered. Such needs lead to the development of DNA microarrays; tiny gene-based sensors traditionally prepared on coated glass microscope slides. The following review is intended to provide historical insight into the advent of the DNA microarray, followed by a description of the technology from both the application and fabrication points of view. Finally, a description of the unmet challenges and needs associated with DNA microarrays will be described to define areas of potential future developments for the materials researcher.

*Director R&D-Schott Nextarion AG,
Ma/005, Otto-Schott-Str. 2,
D-55127 Mainz, Germany
E-mail: sam.conzone@schott.com

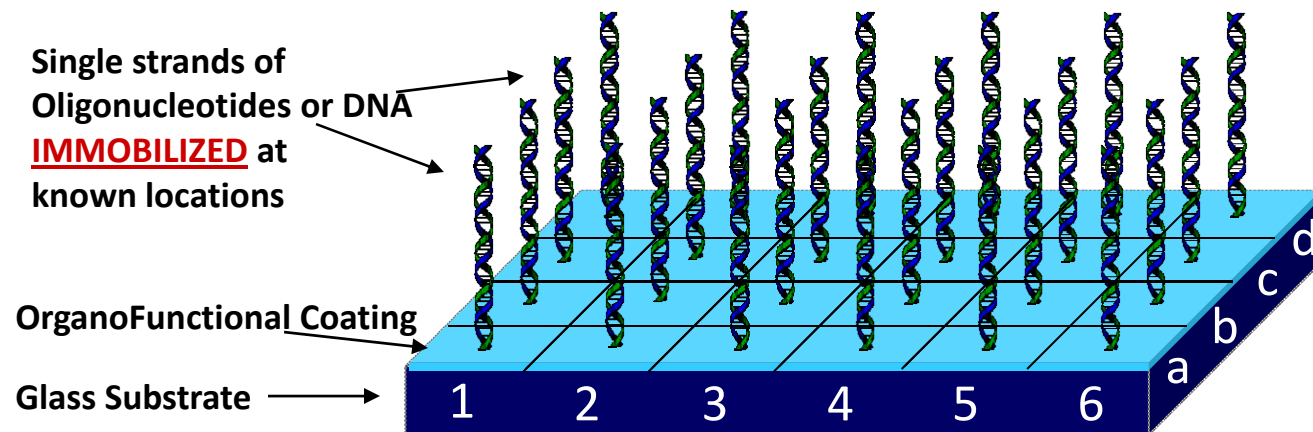
†Director, Materials Research Institute,
The Pennsylvania State University,
195 Materials Research Institute Building,
University Park, PA 16802-6809 USA
E-mail: pantano@ems.psu.edu

Most individuals, outside of academic circles focused on genomics, became aware of the potential commercial, technical, and social importance of the human genome project during the late 1990s. The human genome project was formally initiated in 1990¹ and was expected to last 15 years. It had the major goals of identifying all of the genes in human DNA, determining the sequences of those genes, and storing the information in public databases. However, the project moved quickly from the onset and, by 1998, the Department of Energy (DOE) and the National Institutes of Health (NIH) predicted that the human genome project would be completed by 2003.

The big buzz about biotech

The tremendous success in rapidly mapping and sequencing the human genome (a working draft sequence of the human genome was completed in 2000), has lead many commentators to predict that similar achievements would follow on the applications side, leading to unprecedented discoveries related to human health^{2,3}. Gaudy promises of high-tech clinics with the ability to prescribe drugs based on the genetic make-up of the patient were well ahead of their time. This normal lag from discovery (the sequenced human genome) to true applications (genetically engineered drugs) is partially attributable to the lack of tools, which could enable researchers to utilize effectively the tremendous amount of information that was generated during the human genome project.

DNA Microarray: a glass-based biological sensor

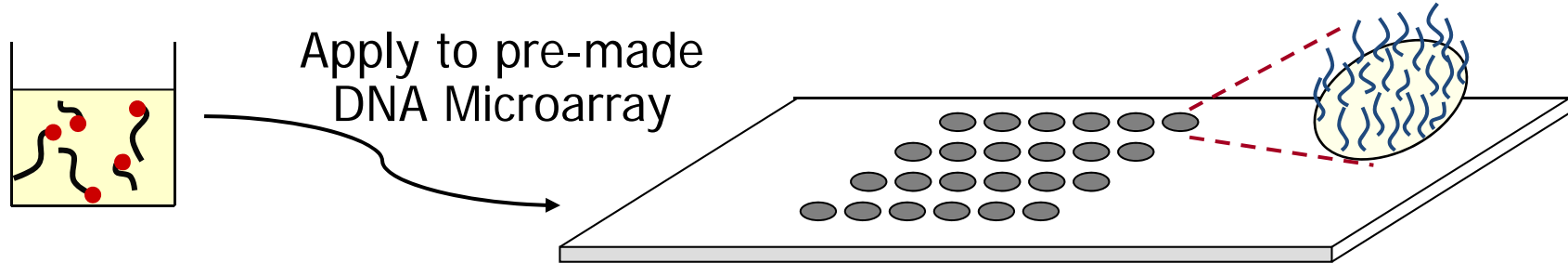


glass substrates provide:

- chemical inertness
- optical platform
- low fluorescence background
- flatness and smoothness
- low cost!

Biomaterials and Bionanotechnology

DNA Microarrays (Gene Chips for sequencing)

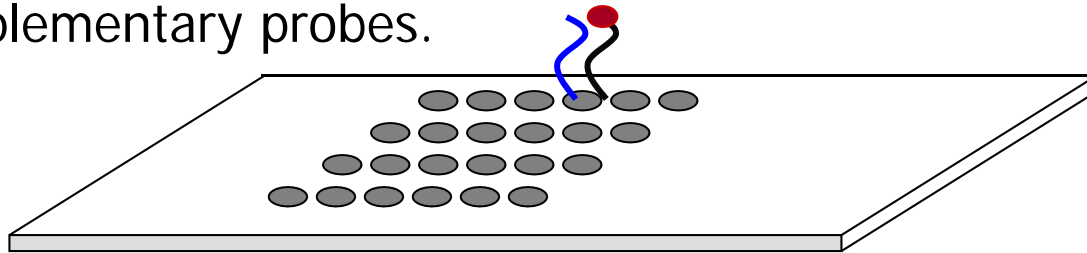


Unknown DNA solution with fluorescent dyes.

Each spot contains identical DNA probes of different **known** sequence.

Laser Confocal Scan

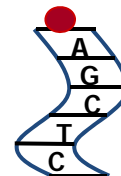
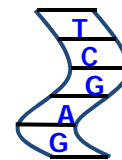
Unknown DNA molecules attach to their complementary probes.



The sequence of the unknown strand is now determined.

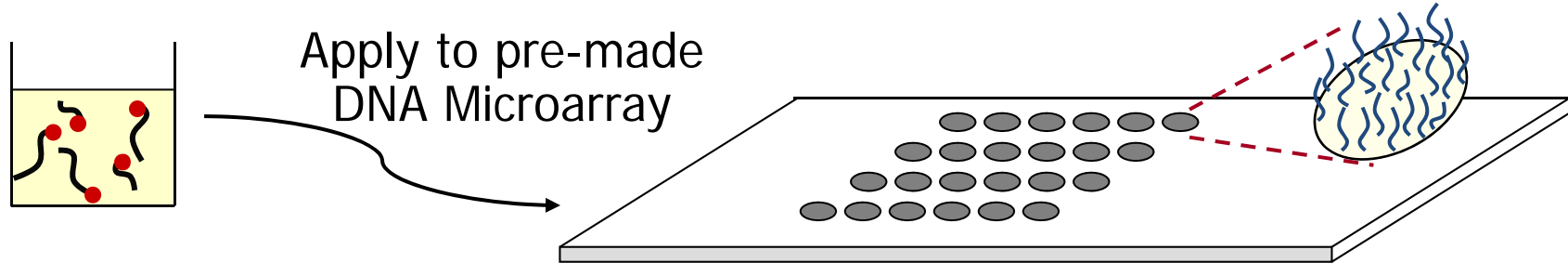
i.e.

Array probe



Unknown probe

DNA Microarrays (Gene Chips for sequencing)

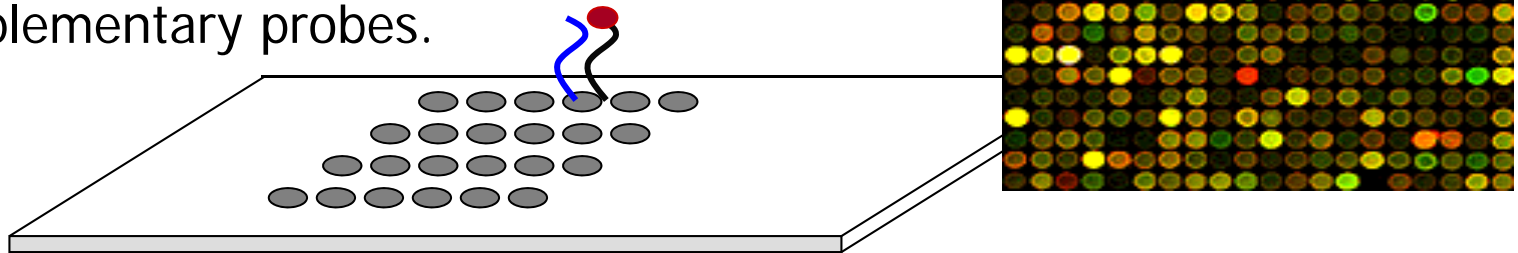


Unknown DNA solution with fluorescent dyes.

Each spot contains identical DNA probes of different **known** sequence.

Unknown DNA molecules attach to their complementary probes.

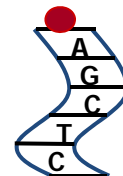
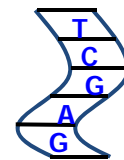
Laser Confocal Scan



The sequence of the unknown strand is now determined.

i.e.

Array probe



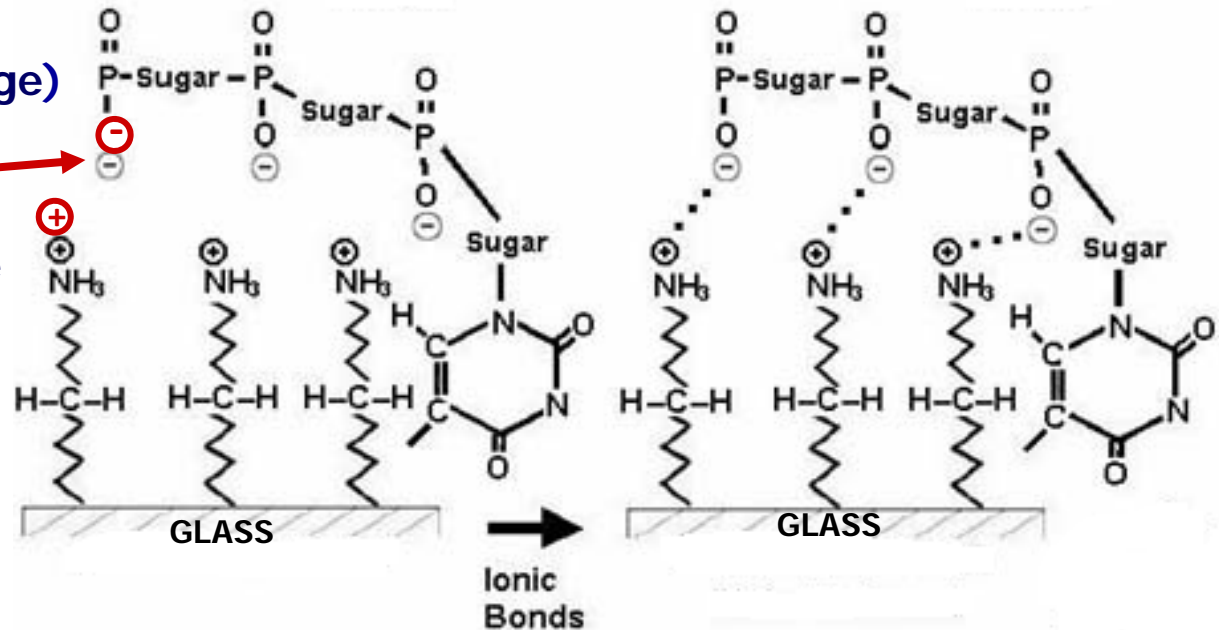
Unknown probe

Immobilization of Unmodified DNA to glass substrates

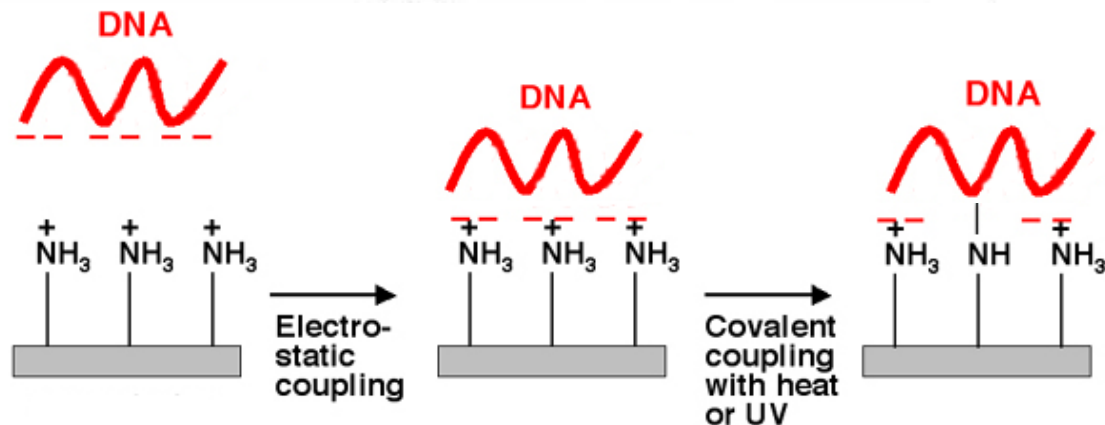
Phosphate-Sugar
DNA backbone
(carries negative charge)

electrostatic
attraction

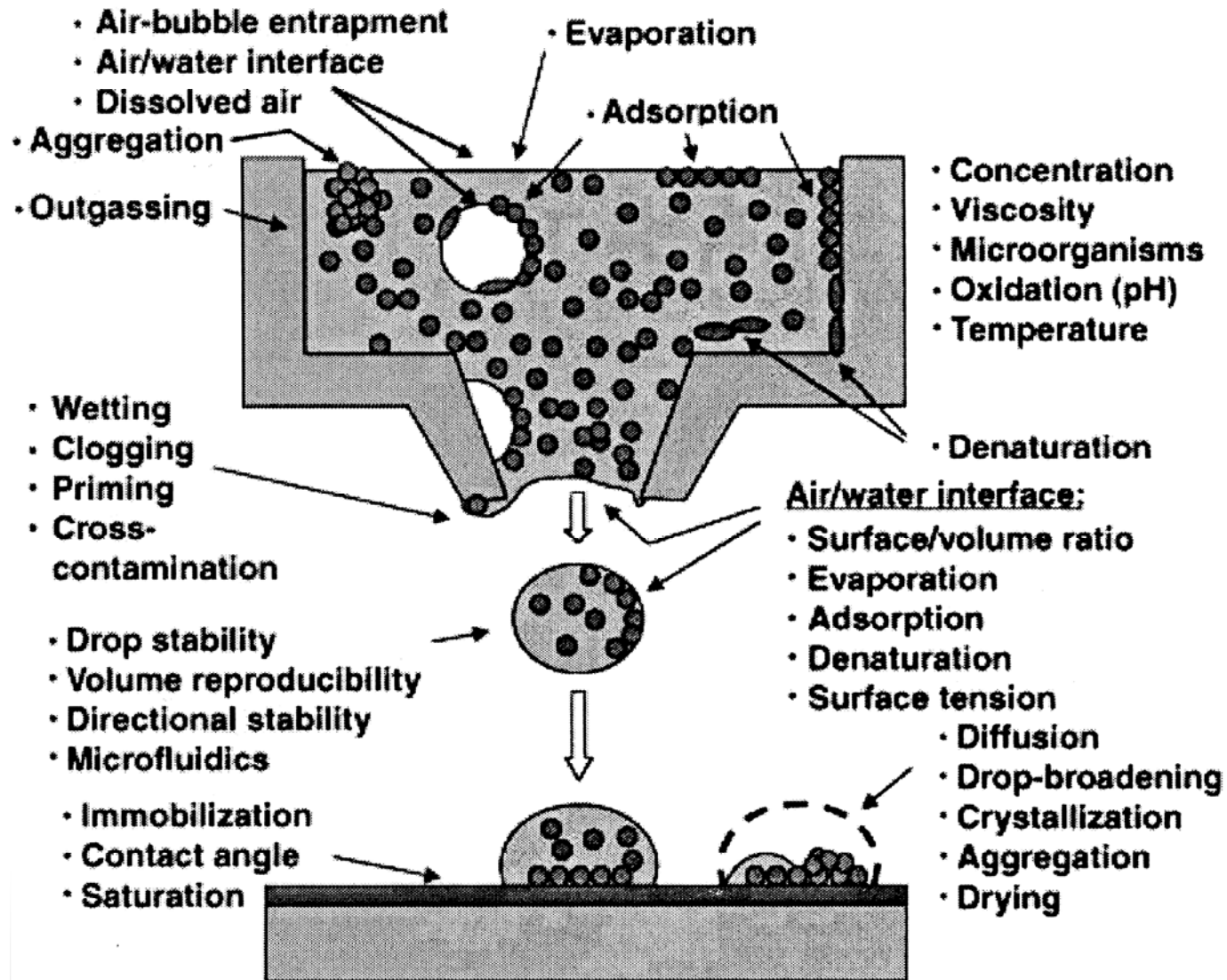
functional amine
group- NH_3^+



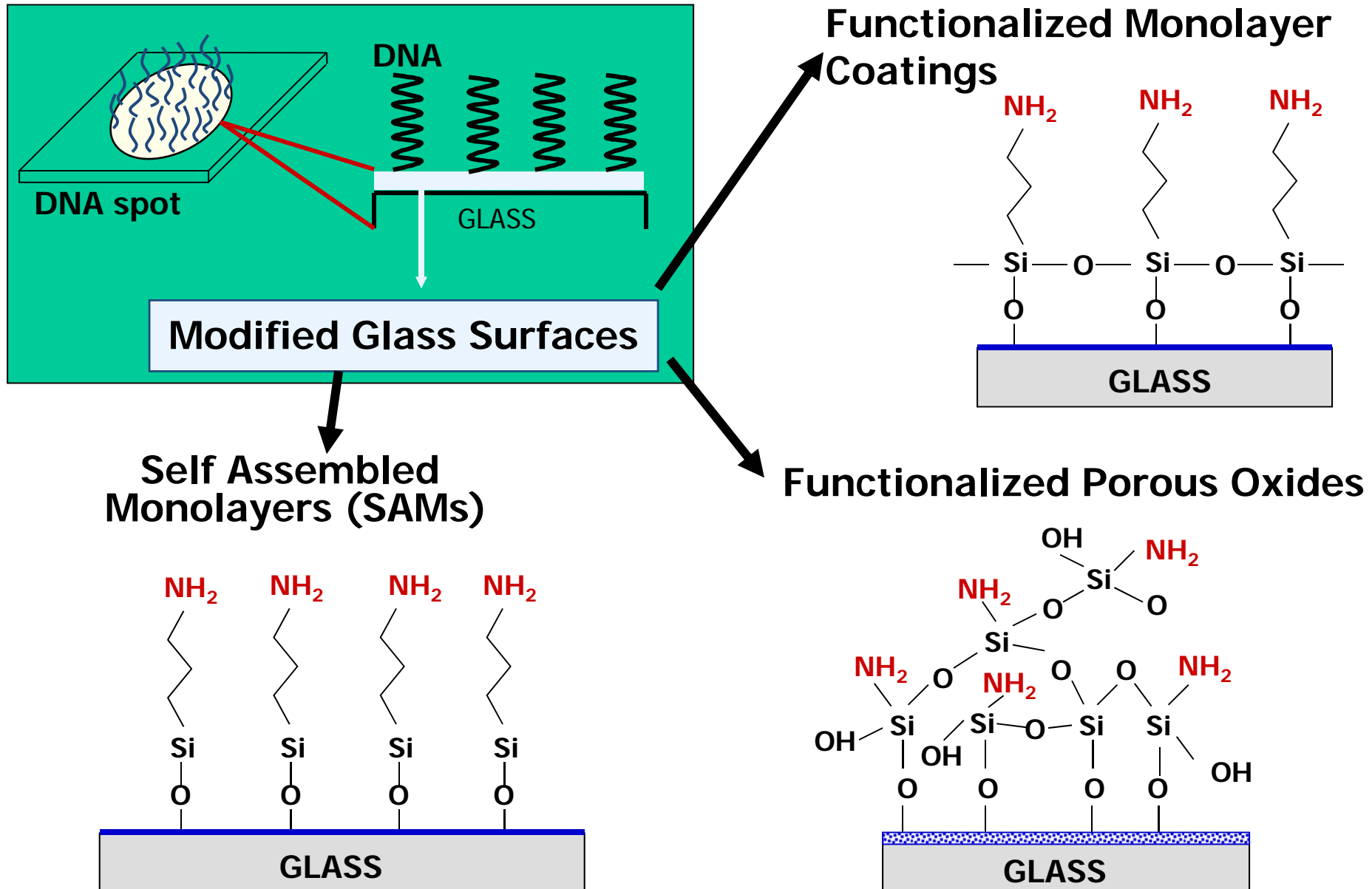
Unmodified DNA strands carry intrinsic $(\text{PO}_4)^{3-}$ groups; glass surfaces functionalized with protonated amino groups (NH_2) can be used for their initial immobilization.



Physical Chemistry/Engineering of the Microspotting Process



MODIFICATION of GLASS for DNA ATTACHMENT

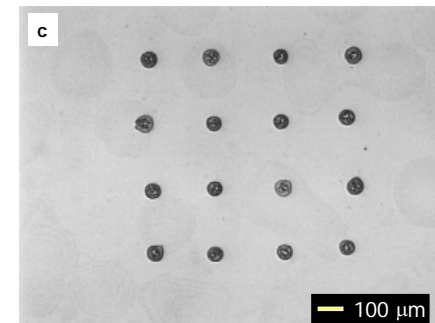
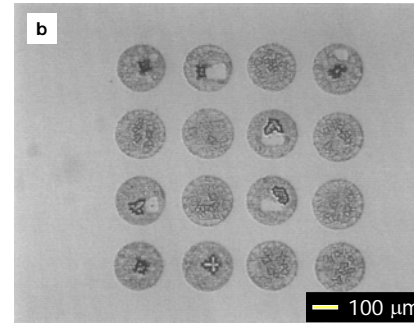
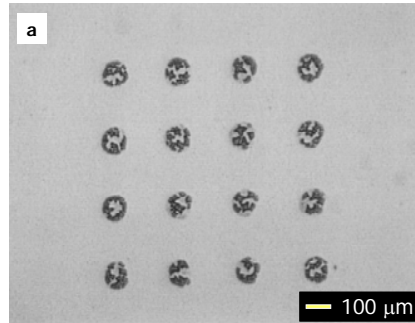


**Aminosilane
(APS)**

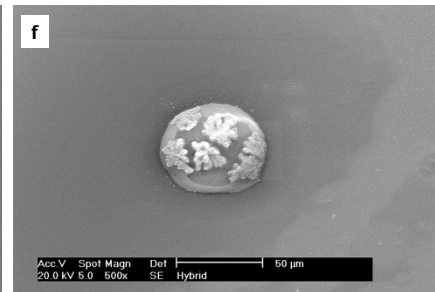
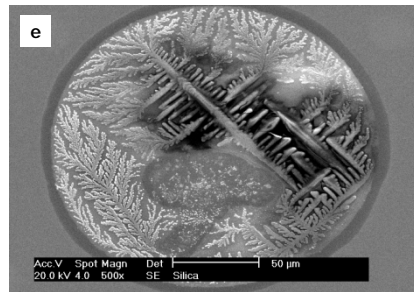
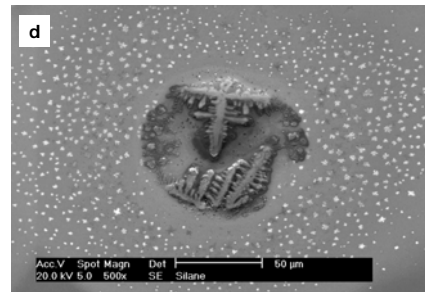
**APS-treated sol/gel
derived porous silica**

**Hybrid sol/gel derived
APS-functionalized silica**

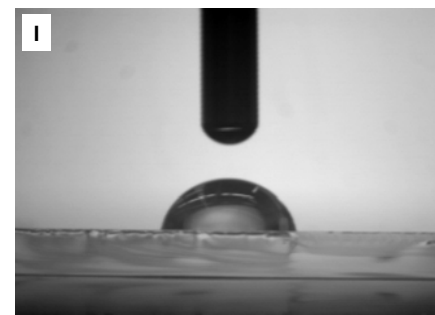
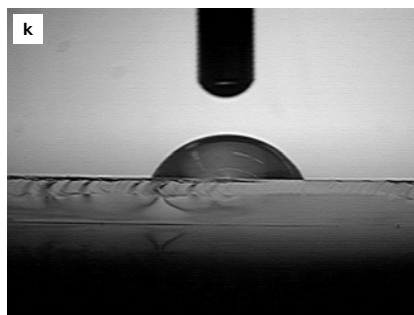
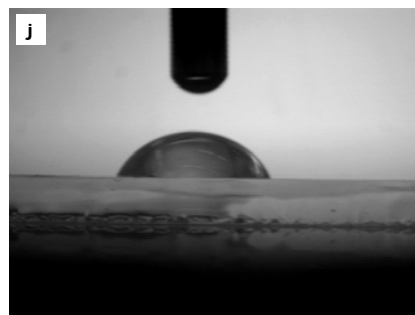
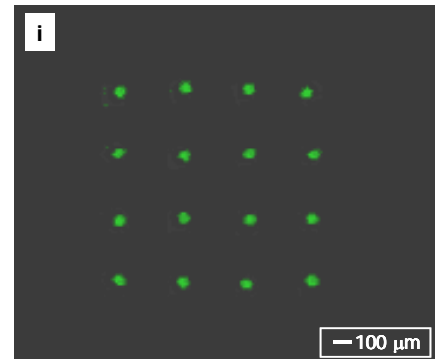
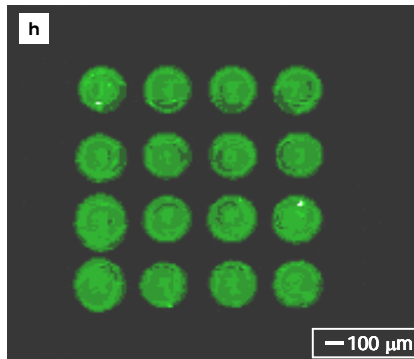
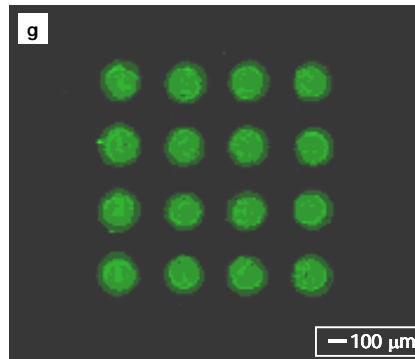
Optical microscopy



SEM



Confocal Laser
Scanning



Code 8161 - 52% PbO, 39% SiO₂, 5% K₂O, 2% Rb₂O and 2% BaO.

The acid etch was brief and utilized an 0.10 N HCl solution. The hydrogen reduction took 10 h at 450-500°C.

These surface layers can exhibit resistivity of ~ an ohm-cm and secondary electron yields up to 3.5.

Electron Emission Glasses

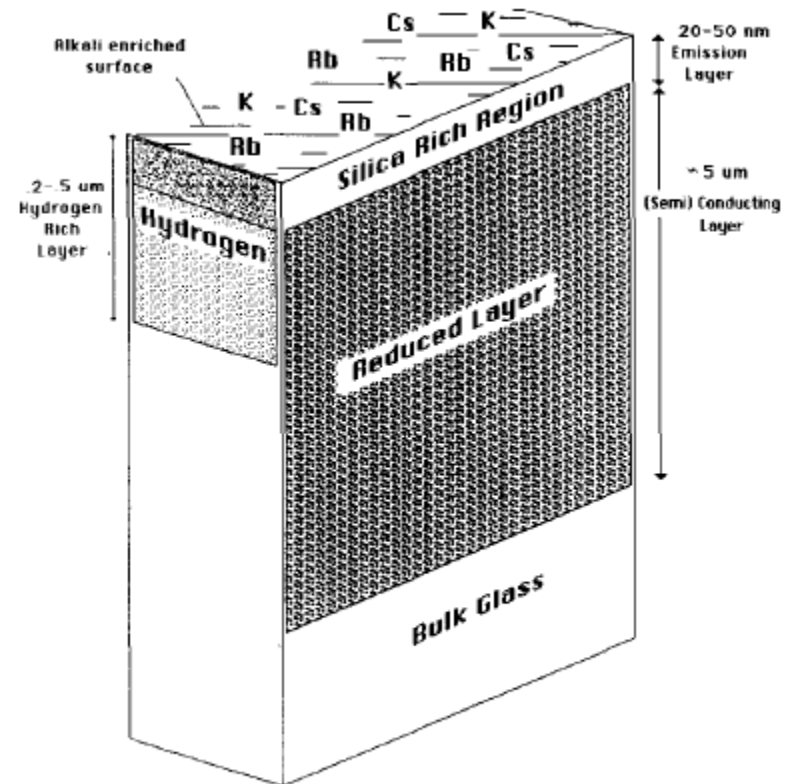
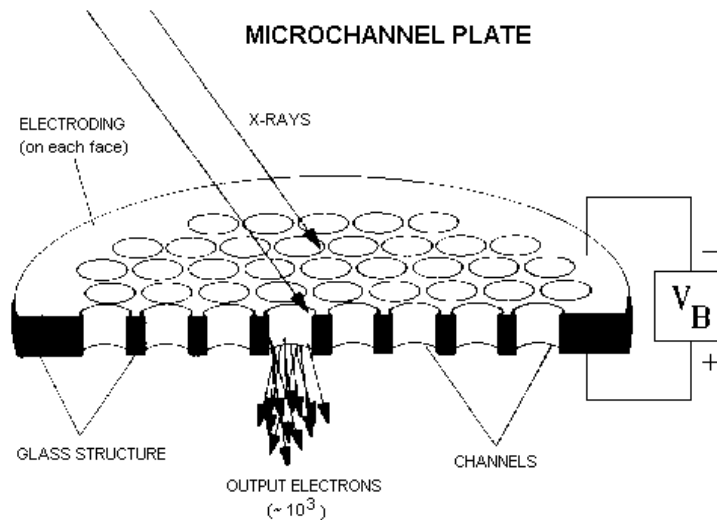


Fig. 5. Schematic representation of a typical acid-etched and reduced alkali-lead silicate glass surface; not to scale.

(Cs,Rb) - Lead Silicate

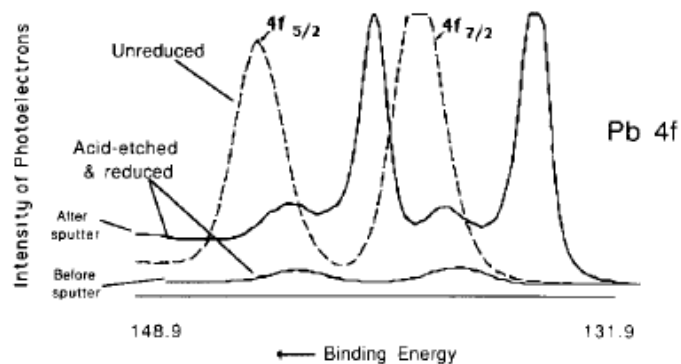


Fig. 4. High-resolution XPS spectra of the Pb 4f line after treatment of the (Cs, Rb)-glass; the spectra of a clean fracture surface is shown for reference.

(Cs,Rb) - Lead Silicate

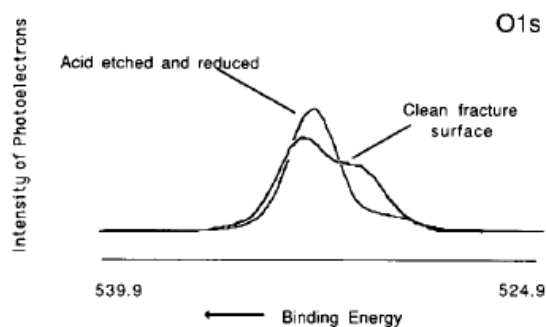
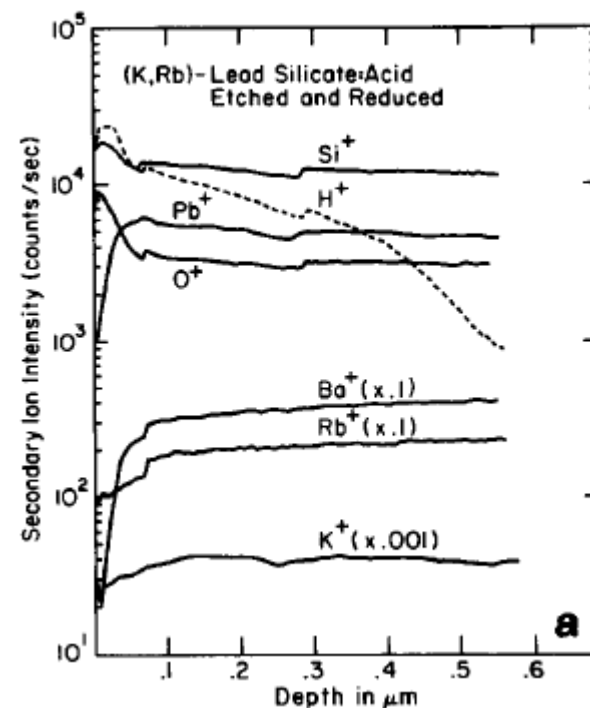
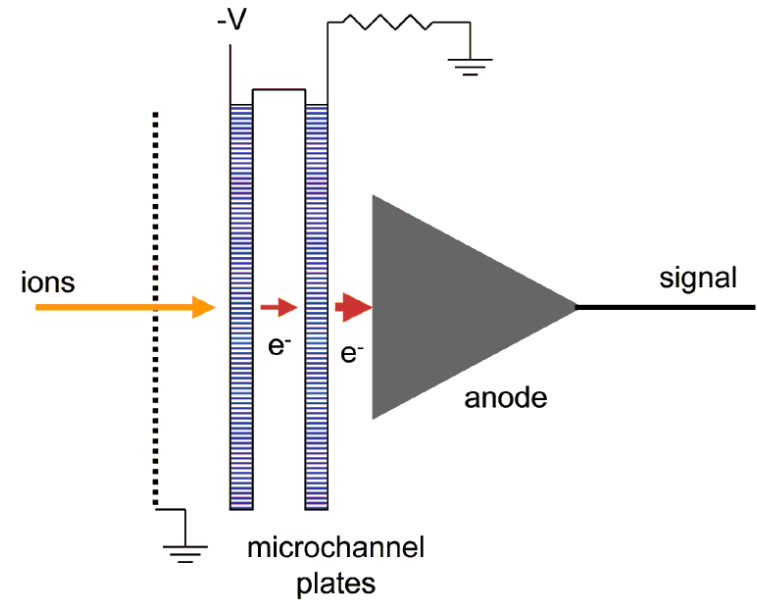
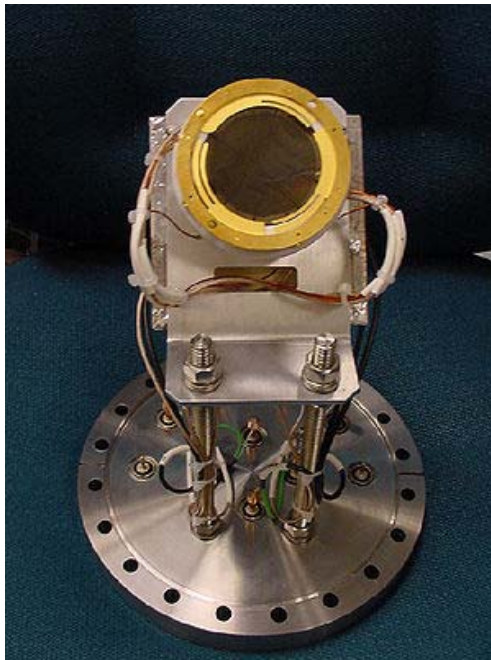


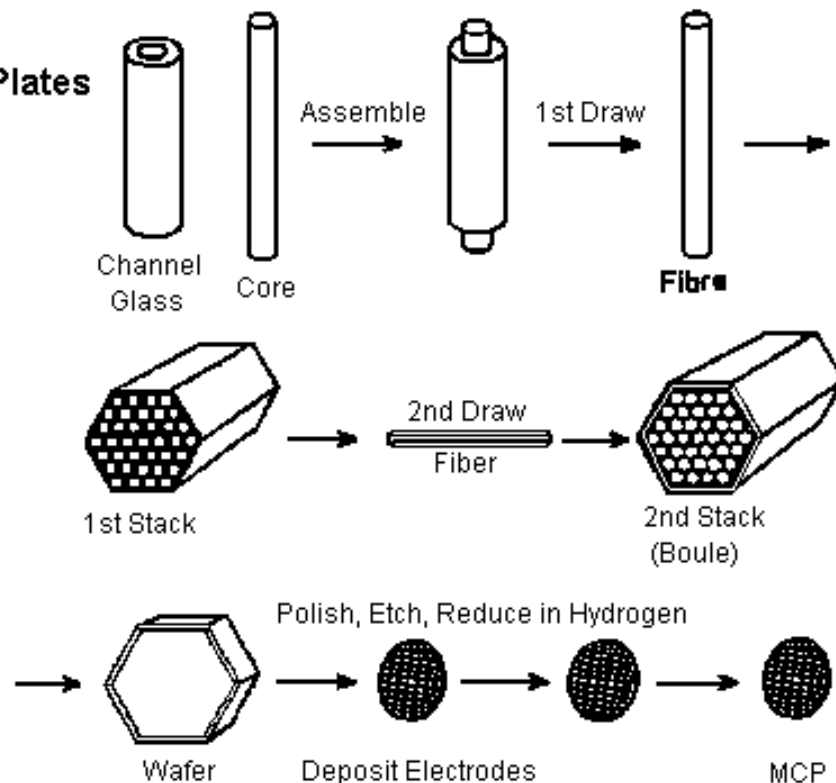
Fig. 3. High-resolution XPS spectra of the O1s line after treatment of the (Cs, Rb)-glass; the reference spectra of a clean fracture surface shows a shoulder at lower binding energy due to non-bridging oxygen.



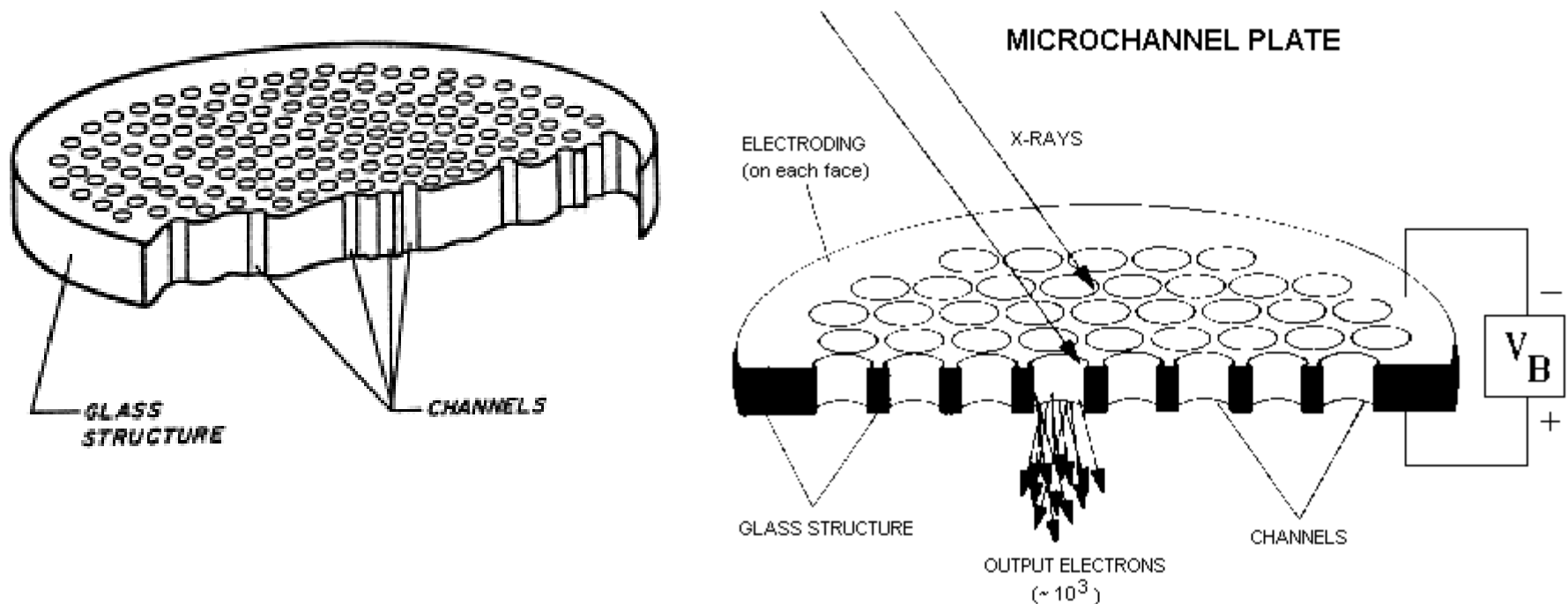


A hollow billet of lead oxide cladding glass is mechanically supported by the insertion of a rod of etchable core glass and then pulled through a vertical oven, producing a "first draw" fiber of approx. 1 mm diameter. Lengths of first draw fiber are then stacked (usually by hand) in a hexagonal array which is itself drawn to produce a hexagonal "multifiber". Lengths of multifiber are stacked in a boule and fused under vacuum. The boule is sliced and polished to the required thickness and shape. The solid core is then etched away, leaving the channel array to be fired in a hydrogen oven to produce a semiconducting surface layer with the desired resistance and secondary electron yield. (Source: Philips Photonics)

Fabrication of Microchannel Plates



A single x-ray photon interacting in a channel of the MCP produces a charge pulse of about 1000 electrons that emerge from the rear of the plate. Since the individual tubes confine the pulse, the spatial pattern of electron pulses at the rear of the plate preserve the pattern (image) of x-rays incident on the front surface. When coupled to an additional MCP and an electronic readout and display the MCP becomes an x-ray image intensifier. The same microchannel plate technology is used to make visible light image intensifiers for night vision goggles and binoculars.

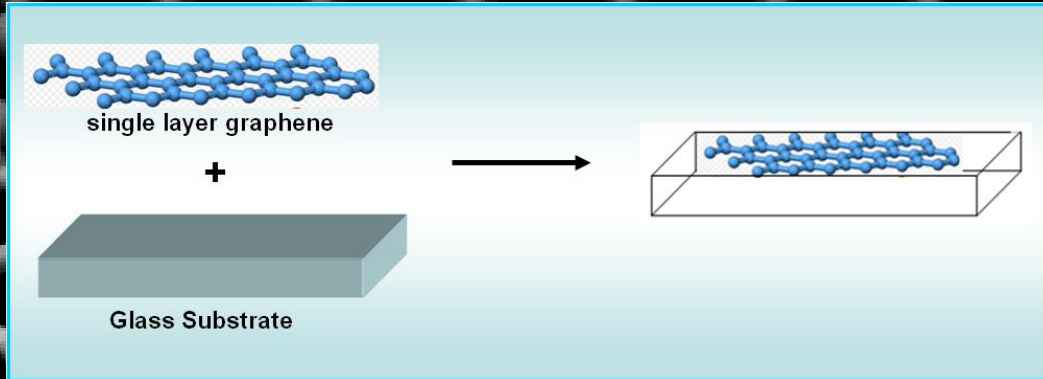




Nanoscale Carbon Coatings for Glass

Carlo Pantano, Hoikwan Lee, Ram Rajagopalan and Josh Robinson
Materials Research Institute
Penn State University

Nanoscale Carbon Coatings for Glass



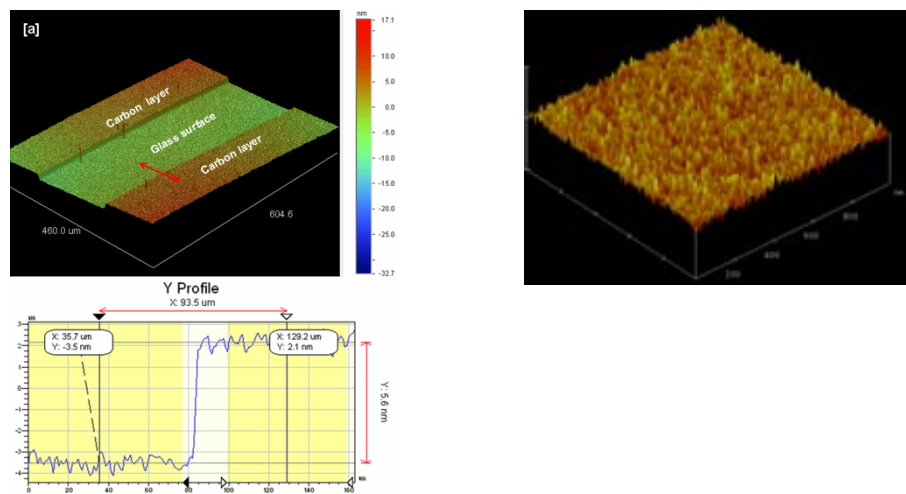
a potentially multi-functional coating

- water barrier
- low friction
- electrical conductivity
- high contact angle

The long-range goal is to deposit or grow this layer on glass to enhance surface properties and add functionality.

Organic Precusors		Before Pyrolysis (nm)	After Pyrolysis at 800°C (nm)	After Pyrolysis at 700°C (nm)
Polyfurfuryl Alcohol (PFA)	0.5wt%	9.60±0.15	3.28±0.04	5.7
	1wt%	12.88±0.08	3.38±0.06	
	5wt%	53.31±0.17	10.04±0.05	
Coal-Tar-Pitch (CTP)	0.5wt%	16.68±0.15	3.27±0.13	3.6
	1wt%	20.94±0.81	4.60±0.18	
	5wt%	81.66±1.69	5.77±0.15	
Photoresist (1805)	(10:1)	13.39±0.18	2.68±0.05	4.6
Thickness Measurement		Ellipsometry		Optical Profilometry

Thin carbon layers on the order of 3 – 6 nm in thickness were formed on glass substrates



SURFACE ROUGHNESS

Polymer Content (wt%)	PFA (nm)	CTP (nm)	Photoresist(1805) (nm)
0.5/(10:1)	0.182±0.017	0.341±0.110	0.180±0.021
1	0.190±0.027	0.257±0.136	
5	0.225±0.028	0.293±0.036	

Contact angle measurements

Precursor	Contained FPA (wt%)	Contact Angle (degrees)
Polyfurfuryl Alcohol	0.5	80.78±2.55
	1	80.55±3.92
	5	79.96±2.39
Coal-Tar Pitch	0.5	79.56±4.22
	1	77.34±1.75
	5	
Photoresist	10:1	85.33±2.19
AF45 Glass	-	47.56

Contact angle of water on pristine AF45 glass

[a]

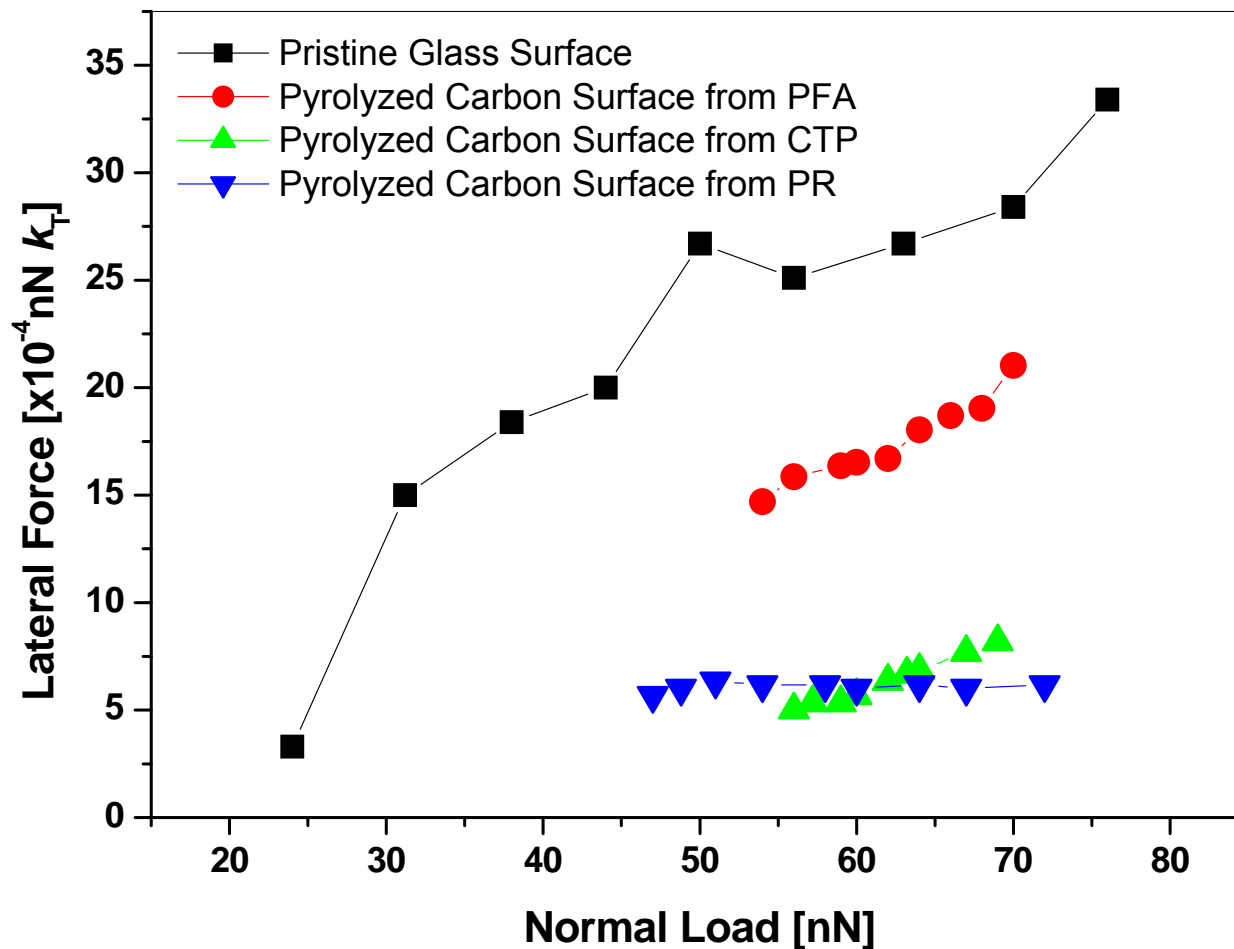


Contact angle of water on carbon coated AF45 glass

[b]

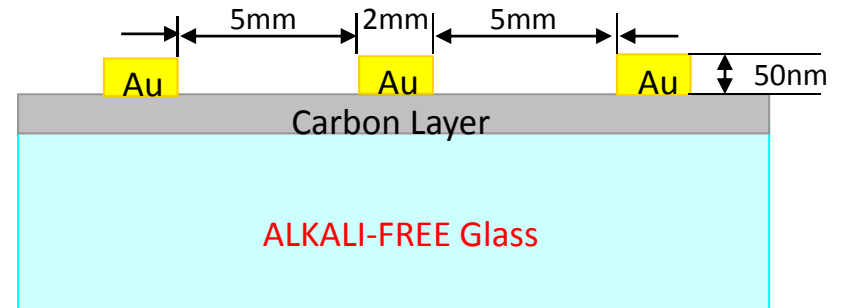


Measurement of frictional force using AFM



Measured frictional force of carbon coated glass was five times lower than the pristine glass surface

Electrical Properties



Temperature (oC)	Electrical Properties	
(2:1) 1805 at 700°C with vacuum	Rs (sheet resistance)	$1.3 \times 10^{-1} \Omega/\text{square}$
	P(Bulk resistivity)	$1.3 \times 10^{-6} \Omega \text{ cm}$
	Electric conductivity	$7.69 \times 10^5 \text{ Scm}$
(2:1) 1805 at 800°C with vacuum	Rs (sheet resistance)	$6 \times 10^{-2} \Omega/\text{square}$
	P(Bulk resistivity)	$6 \times 10^{-7} \Omega \text{ cm}$
	Electric conductivity	$1.67 \times 10^6 \text{ Scm}$
1803 at 800°C with Argon gas atmosphere Reference (thickness :440nm)	Rs (sheet resistance)	$5.03 \times 10 \Omega/\text{square}$
	P(Bulk resistivity)	$2.2 \times 10^{-3} \Omega \text{ cm}$
	Electric conductivity	$4.54 \times 10^2 \text{ Scm}$

Investigating the effect of sodium near the glass/polymer interface

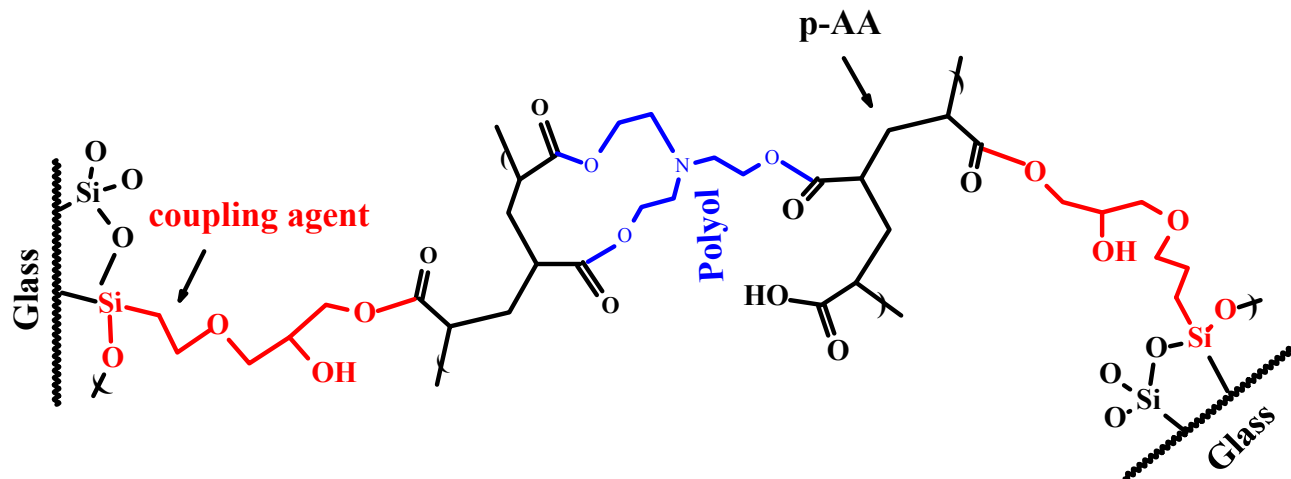
Joy Banerjee, Carlo Pantano (Penn State)

James Hamilton (Johns Manville)

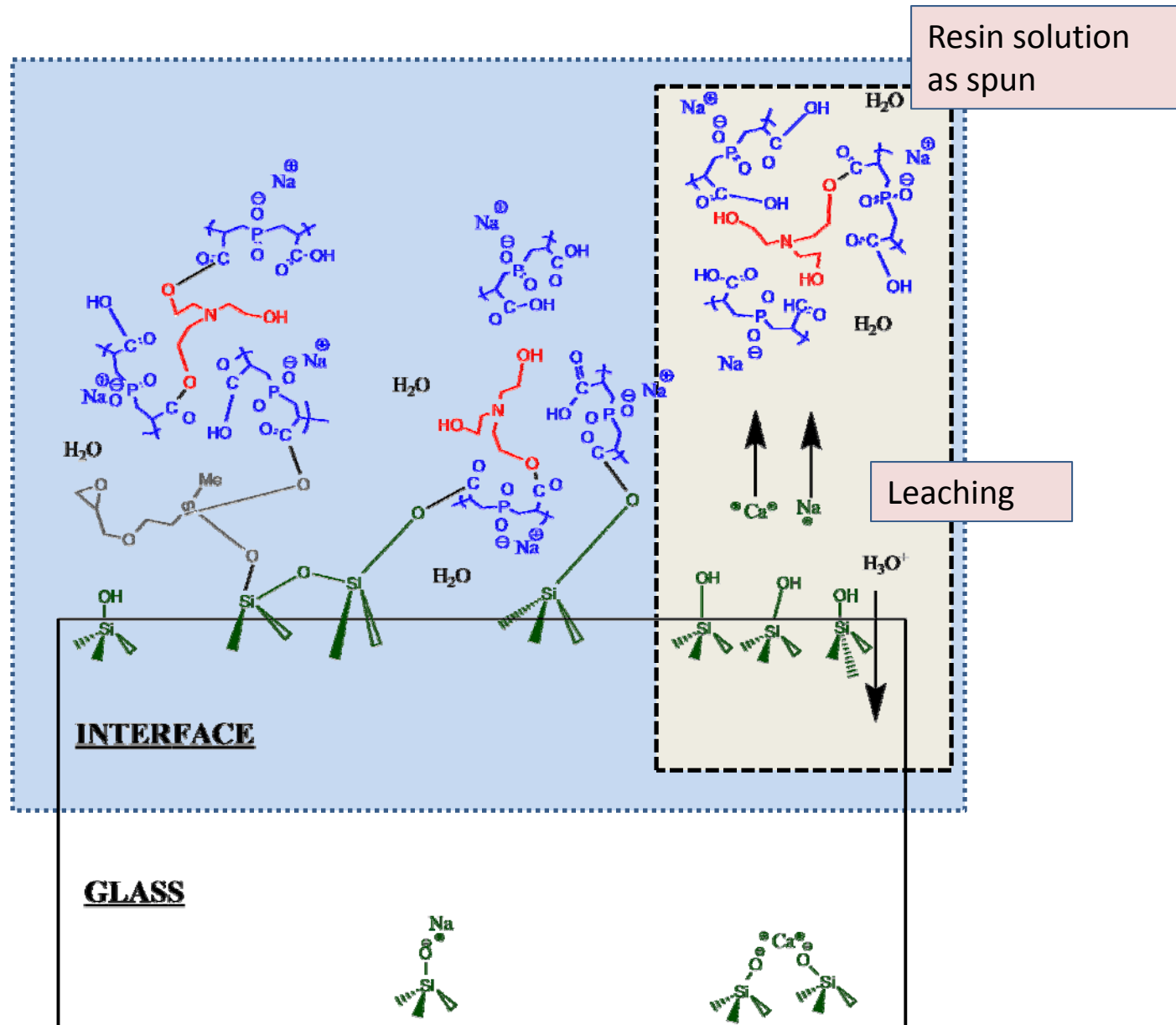
Scope

Interfacial chemistry

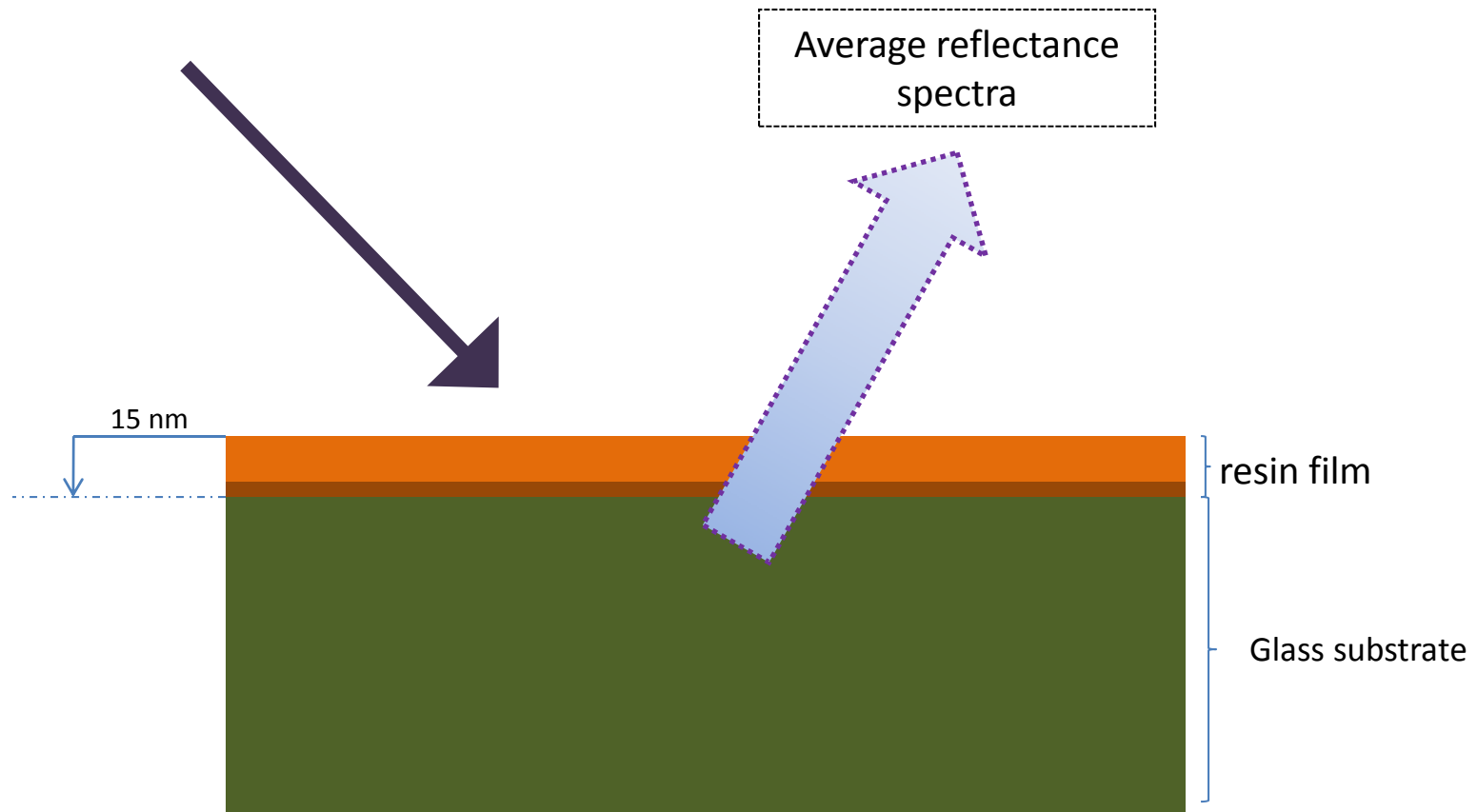
- Between glass surface and “green” (water-based) polymers
- Effect of bulk/surface glass composition
- Effect of polymer pH and processing conditions



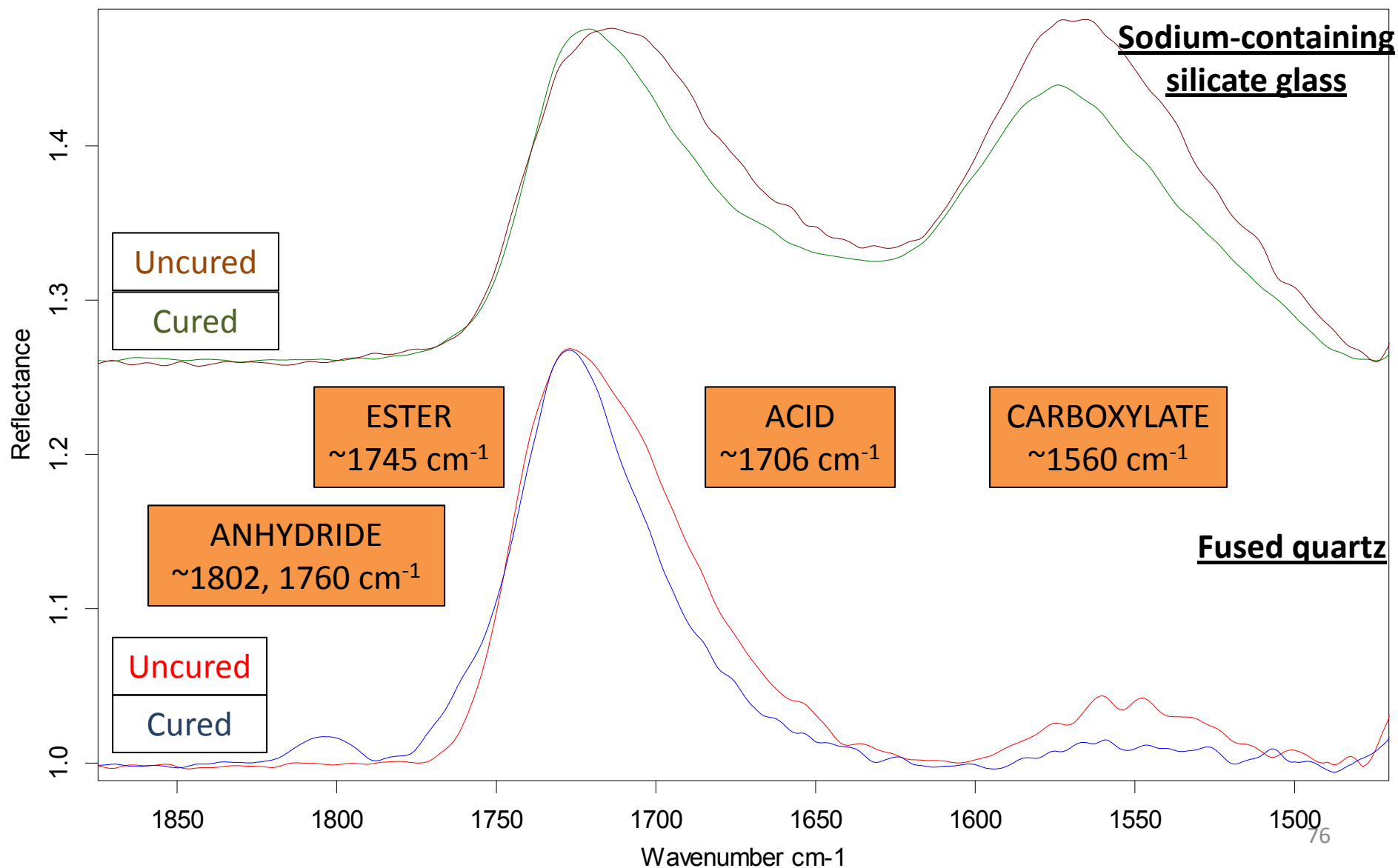
Resin on sodium-rich glass as-spun



Infrared Reflectance Spectroscopy of thin films

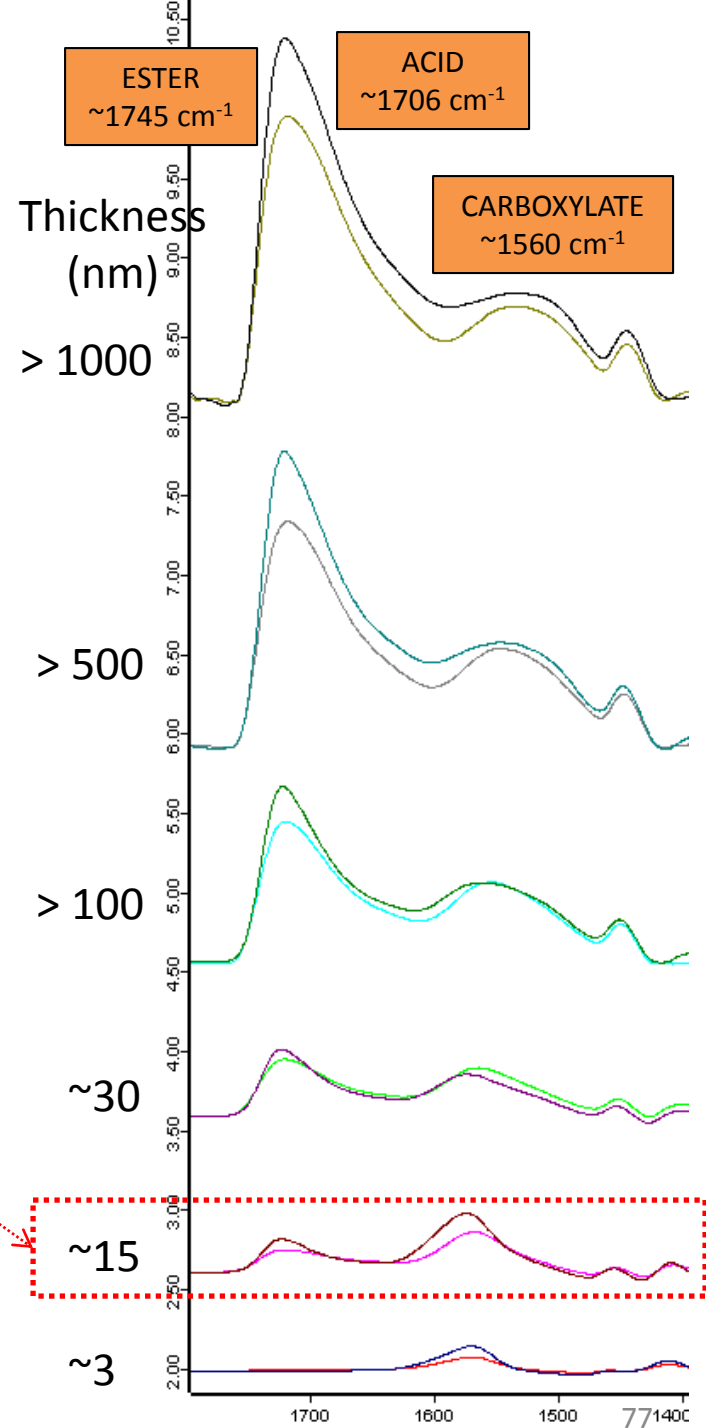
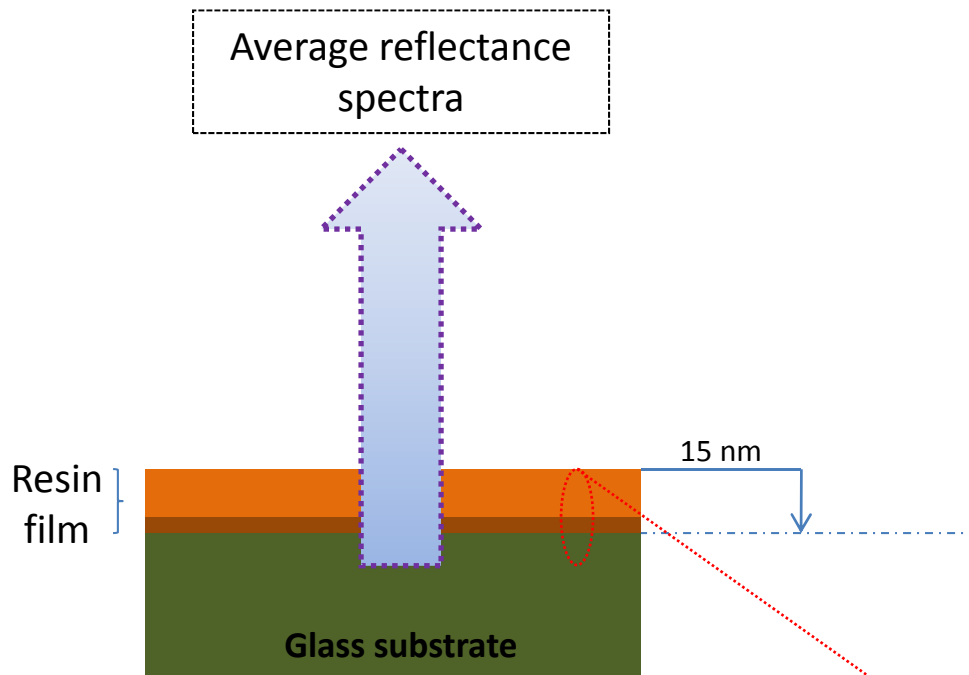


Resin thin film on glass (film thickness: 15nm)



○ Resin interacts differently with JM901 versus fused quartz, primarily with carboxylate formation

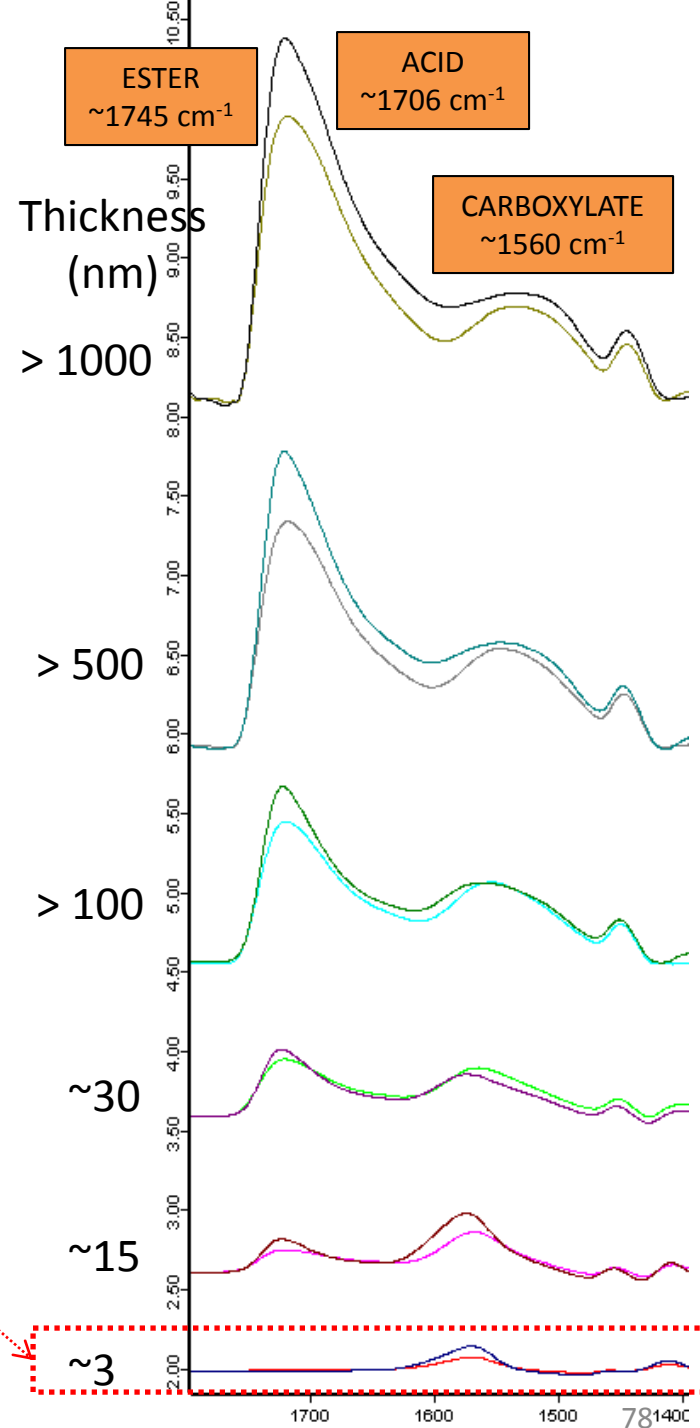
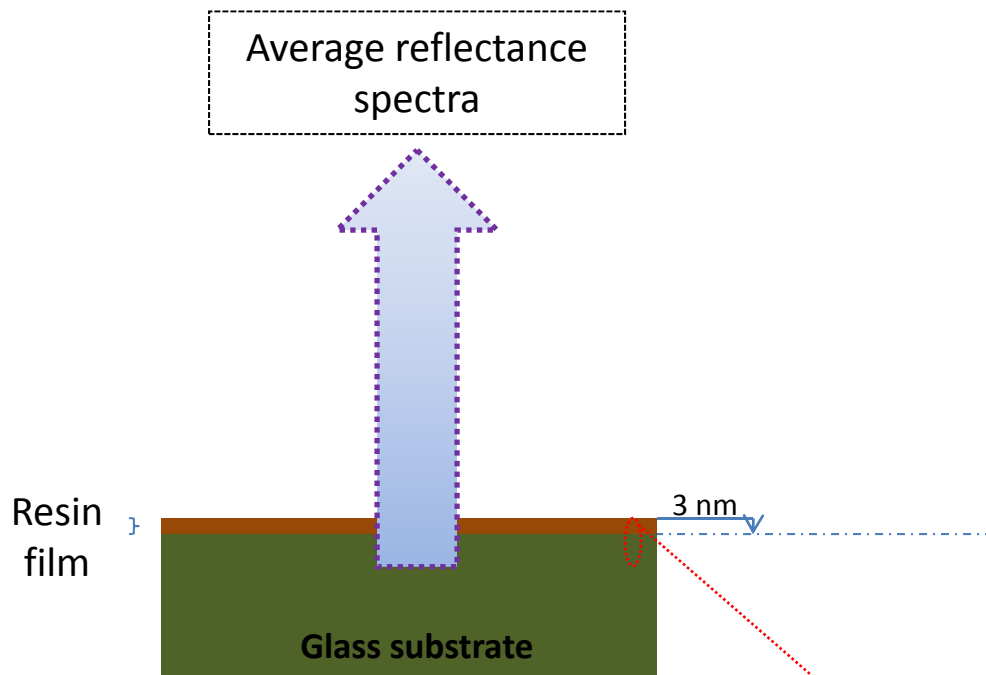
Resin on JM901 (varying thickness)



Higher intensity at acid/ester peak: cured 190C/1h

Lower intensity at acid/ester peak: dried 15h

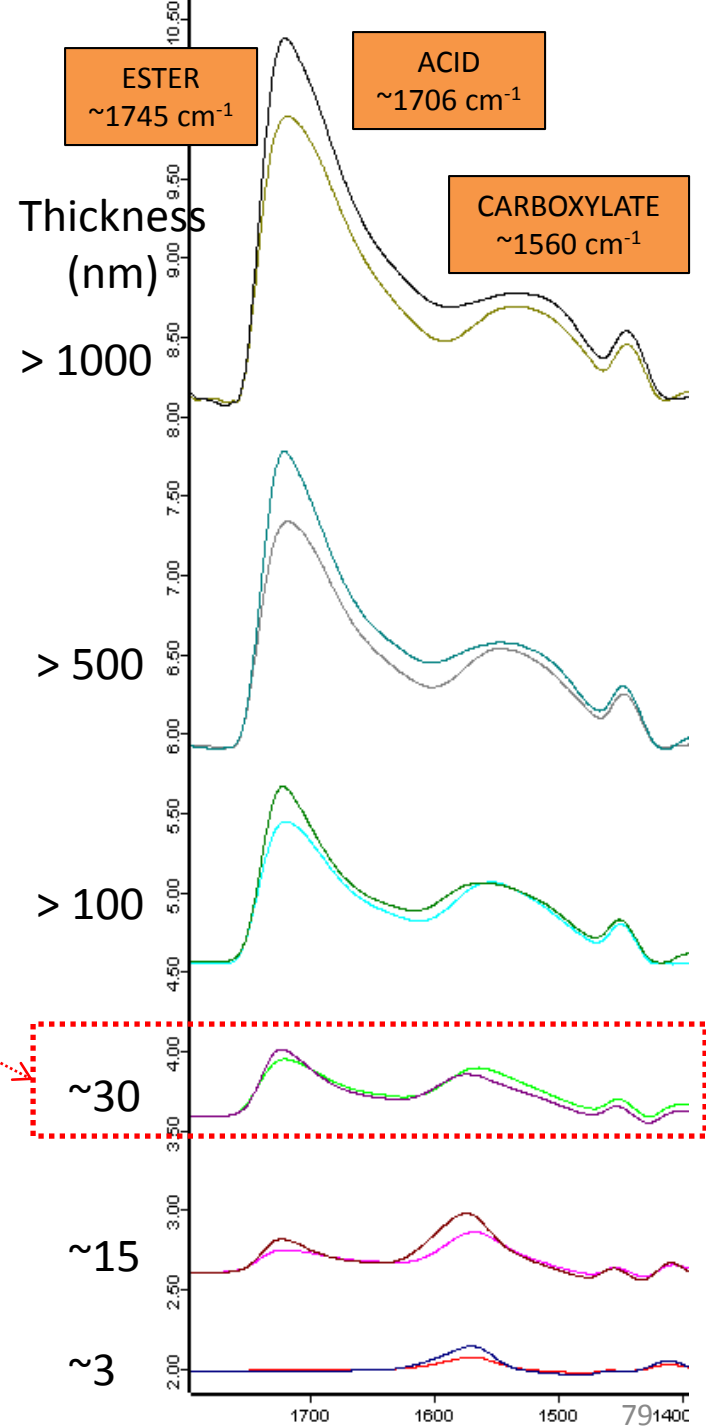
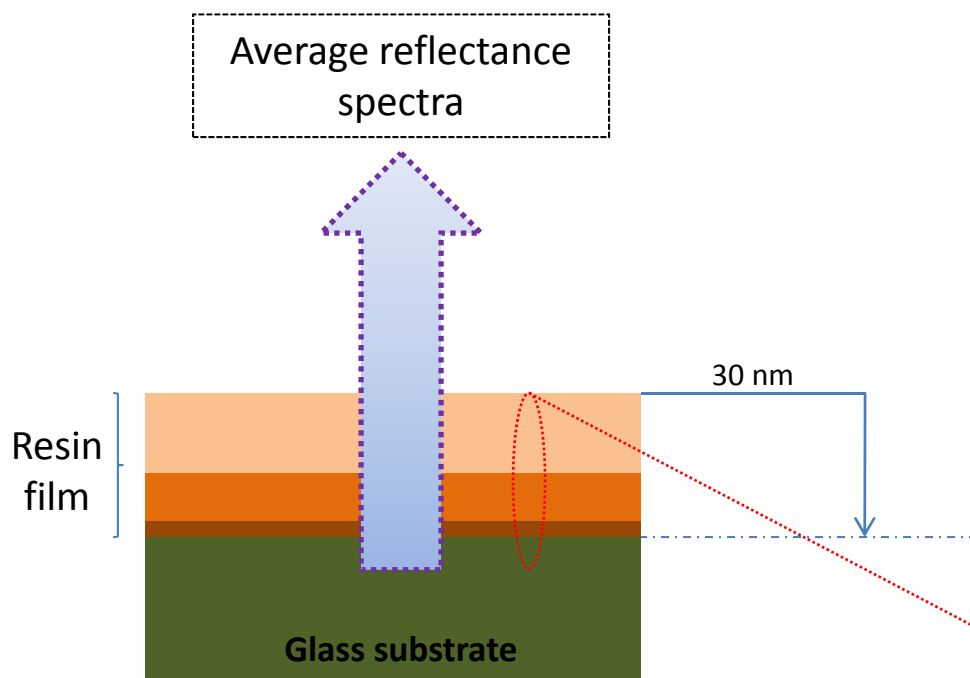
Resin on JM901 (varying thickness)



Higher intensity at acid/ester peak: cured 190C/1h

Lower intensity at acid/ester peak: dried 15h

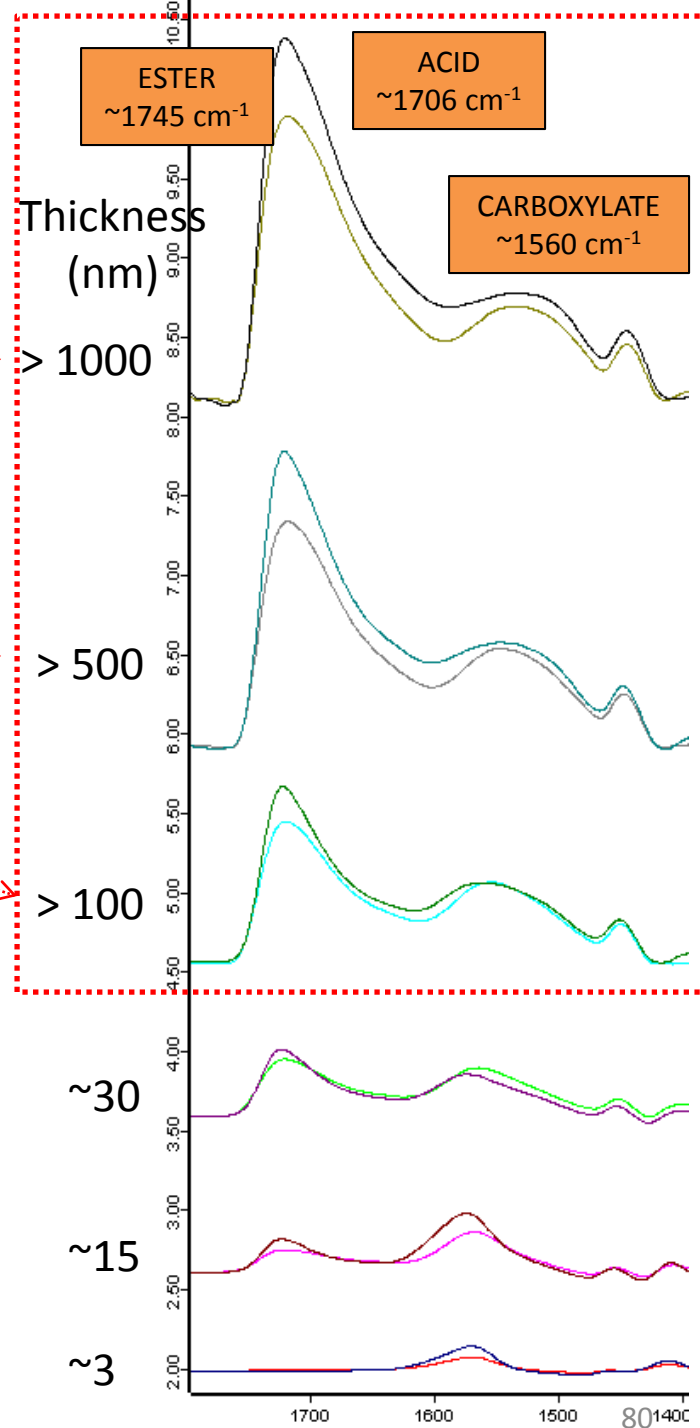
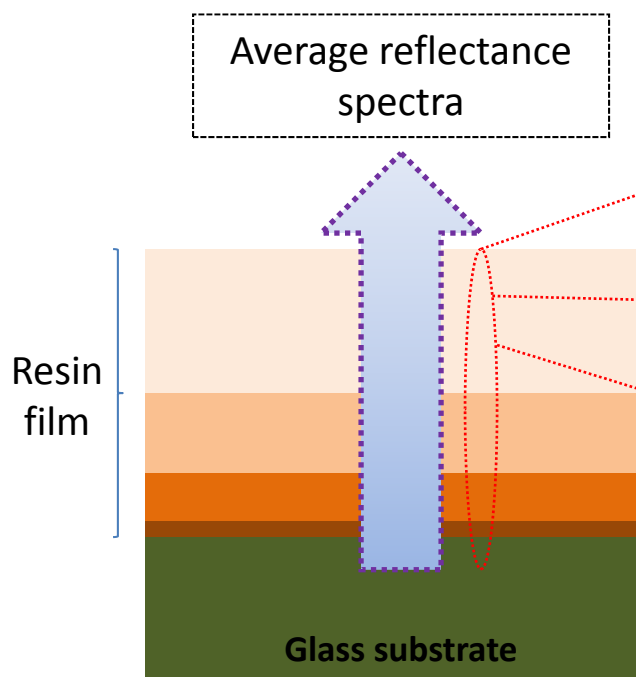
Resin on JM901 (varying thickness)



Higher intensity at acid/ester peak: cured 190C/1h

Lower intensity at acid/ester peak: dried 15h

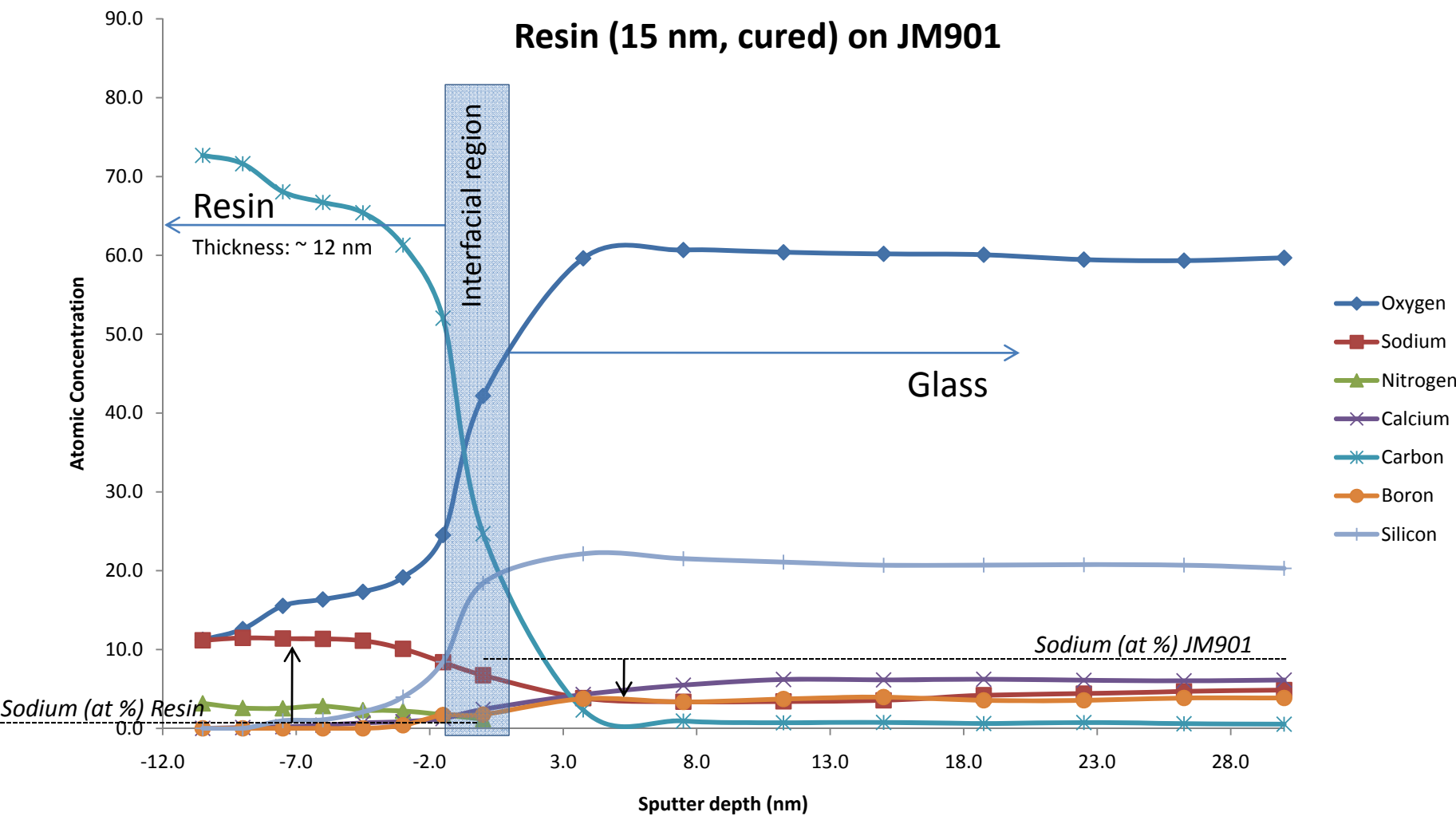
Resin on JM901 (varying thickness)



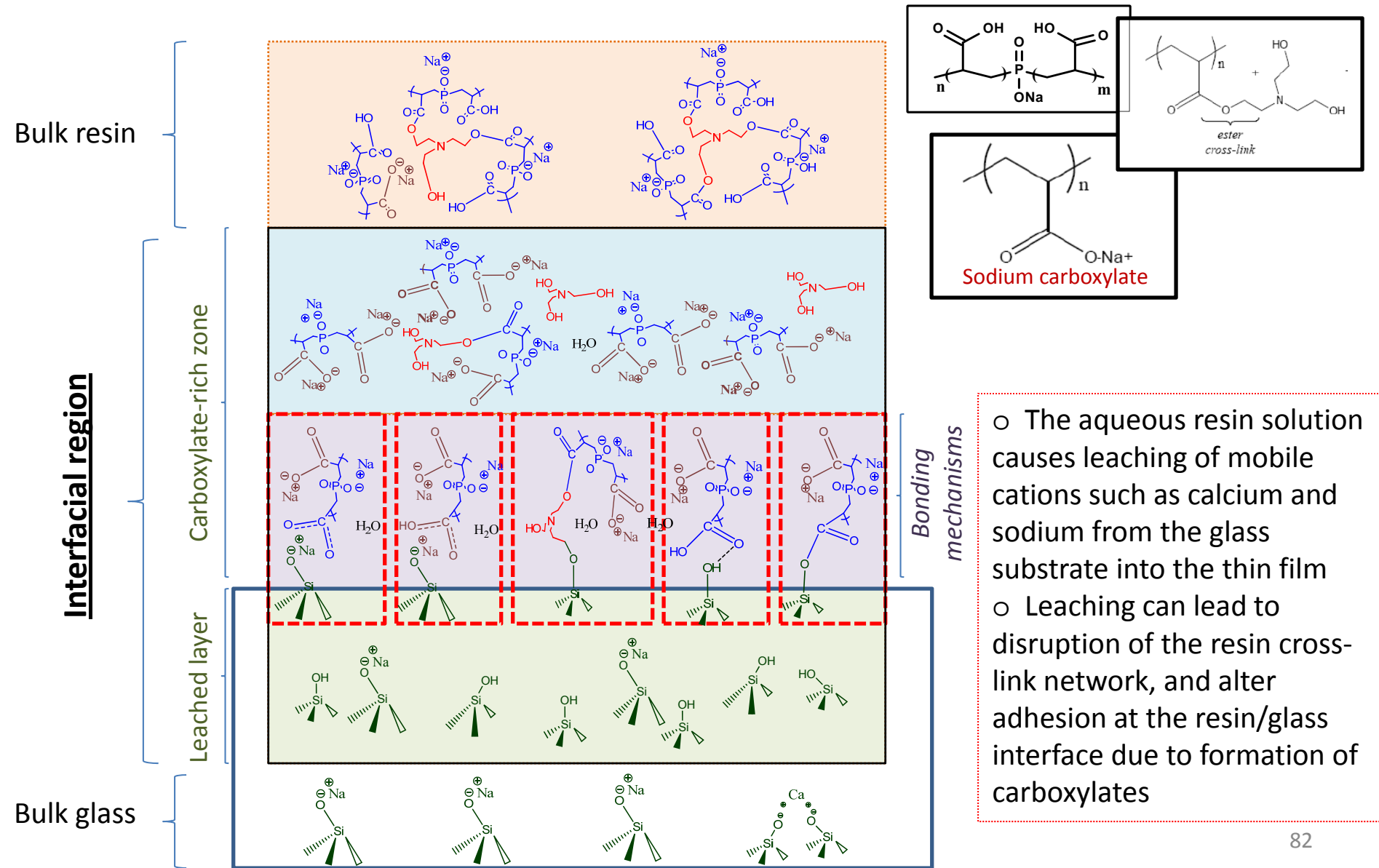
Higher intensity at acid/ester peak: cured 190C/1h

Lower intensity at acid/ester peak: dried 15h

Does sodium transfer from glass into the resin?



What is going on near the interface?



Our current interface model with proposed bonding sites

